WORKSHOP ON PALEOCLIMATIC ASPECTS OF EL NINO/SOUTHERN OSCILLATION

MAY 2 - 4, 1990

BOULDER, COLORADO

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INSTITUTE OF ARCTIC AND ALPINE RESEARCH

UNIVERSITY OF COLORADO, BOULDER

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HENRY F. DIAZ[1] AND VERA MARKGRAF[2]

ORGANIZERS

[1] NOAA/ERL, 325 Broadway, Boulder, CO 80303

[2] Institute of Arctic and Alpine Research,
University of Colorado, Boulder, CO 80309

AGENDA

Workshop on Paleoclimatic Aspects of El Nino

Wed. May 2

8:30 A.M.	Coffee/Pick up Preprint Materials	
9:00	Welcoming Remarks	-- Dr. R. Palm Dean of the Graduate School -- Dr. M. Meier Director, INSTAAR
9:15	Overview of El Nino/Southern Oscillation	-- D. Enfield
9:45	Atmospheric teleconnections	-- H. Diaz
10:15	Coffee Break	
10:30	A Preliminary record of Southern Oscillation-related activity extending about 1368 years into the past	-- W. Quinn
11:00	Historical ENSO variability in the Australasian region	-- N. Nicholls
11:30	Hydrological effects of ENSO on the Western U.S.	-- D. Cayan
Noon	Lunch	
1:30 P.M.	Model ENSO cycles under late Pleistocene conditions	-- N. Graham
2:00	Coupled GCM simulations of ENSO	-- G. Meehl
2:30	Low frequency changes in ENSO: Evidence for a solar-ENSO connection	-- D. Enfield
3:00	Coffee Break	
3:15	ENSO in the paleoclimate record An Overview	-- V. Markgraf
3:45	Reconstructing the history of interannual climate variability from ice cores	-- L. Thompson

4:15	A comparison of proxy records of ENSO	-- J. Michaelsen
4:45	ENSO signals in forest fire records from the Southwest	-- T. Swetnam
5:15	End of session	

<u>Thurs. May 3</u>

8:30 A.M.	Southern Oscillation extremes reconstructed from tree-rings of the Sierra Madre and Southern Great Plains	-- D. Stahle and M. Cleaveland
9:00	The search for an ENSO signal in Great Salt Lake fluctuations	- P. Kay
9:30	ENSO signals in U.S. Southwest tree-rings	-- D. Meko
10:00	Coffee Break	
10:15	A search for ENSO signals in dendroclimatic reconstruction of past drought in the eastern United States	-- E. Cook
10:45	Tropical cyclone frequency, terrestrial flood frequency and ENSO	-- R. Webb and J. Betancourt
11:15	ENSO indicators in coral from the equatorial Pacific	-- G. Shen
11:45	Oxygen isotope records of the Southern Oscillation from Tarawa Atoll corals	-- J. Cole
12:15 P.M.	Lunch	
1:30	Reconstructing an index of the Southern Oscillation from tree-rings	-- J. Lough
2:00	ENSO signal in drought-sensitive tree-ring records from the American Southwest and Java	- R. D'Arrigo
2:30	Long-term changes in the ENSO cycle as measured in marine sediments	-- R. Anderson

3:00	Coffee Break	
3:15	Sensitivity of natural high resolution records to ENSO variability	-- T. Baumgartner
3:45	Climatic sensitivity of biological components in laminated sediments of the Santa Barbara Basin	-- A. Soutar
4:15	Holocene history of the El Nino phenomenon as recorded in flood sediments of northern coastal Peru	-- L. Wells
4:45	Paleoclimatic signals in laminated Rift-Lake sediments of east Africa	-- T. Johnson
5:15	End of session	

<u>Fri. May 4</u>

8:30 A.M.	Climatic variability in Australian paleoenvironmental records	-- P. Kershaw
9:00	ENSO and the Holocene climates and fire history of New Zealand	-- M. McGlone
9:30	Climate and fisheries: Cause and effect	-- G. Sharp
10:00	Coffee Break	
10:15	Prospects and opportunities in Paleo-ENSO research	-- M. Hughes
10:45	Paleoclimate data management and the NOAA/NGDC paleoclimate program	-- T. Holcombe
11:15	USGS Paleoclimate Program	-- W. Dean
11:45	Closing Remarks	
	Meeting adjourned	

Overview of El Niño/Southern Oscillation

David B. Enfield

NOAA Atlantic Oceanographic & Meteorological Laboratories
4301 Rickenbacker Cswy, Miami, FL 33149 (305-361-4351)

It is probably true that most of today's researchers in the field of El Niño/Southern Oscillation (ENSO) knew relatively little of the subject only 10-15 years ago. Most recently, a large, interdisciplinary group of aficionados has been added to the ENSO stewpot — earth scientists interested in understanding paleoclimatic aspects of the bio-geological record. For them (and many of you), making sense of the plethora of information on this complex subject is one of the challenges and prerequisites to doing paleoclimatic research on ENSO. In this overview I will try to minimize retreading over that which you probably already know from the ample coverage the subject has received. I won't bore you, therefore, with yet another definition, dead fish in Peru, or even the fact that ENSO involves a large scale interaction of ocean and atmosphere in the tropical Pacific. Much of this has been covered in reviews (*Enfield, 1989*). As quickly as possible, let me delve into several subjects that are central to your paleoclimatic participation in the ENSO game:

What is the history of ENSO? How did our understanding of ENSO develop? When was the phenomenon recognized and how did early perceptions differ from those of today? What was the evidence in colonial Peru that enables us to document El Niño episodes as far back as the Spanish conquest?

What are the mechanisms proposed for ENSO? This confusing subject is a key to hypothesizing about ENSO variations that we detect in the prehistorical paleoclimatic record. Is ENSO solely an internal oscillation of the Indo-Pacific ocean/atmosphere system, is it entirely forced by external factors, or does it involve some combination of both? We don't know the answers, but we need to understand the suggestions and the evidence for them.

What are the passive manifestations of ENSO? This subject is alchemy to many researchers, because it lies at the periphery, not the core, of what ENSO is all about, and involves many messy interactions of which models and observations can say little. It is the bread and butter, however, of paleoclimatic research. A particular class of manifestations — teleconnections (*Rasmusson, 1985;*) — is especially important because it enables us to find paleoclimatic evidence for ENSO in many parts of the world. I will mention as many of the relevant impacts as time — and my own limited knowledge — permit, and will give several examples of ongoing investigations and the questions they raise.

Research on ENSO and its climatic impacts is increasing faster than the concentration of carbon dioxide in the atmosphere, giving us some hope for real progress on both problems before the end of the century. Only 15 years ago, however, very little was known of ENSO, beyond the seminal contributions of Bjerknes and the mostly incidental (accidental?) discoveries of others. The El Niño phenomenon as we know it dates back only to the early 1890s, in Peru. Prior to that, it was buried in the oral folklore of fishermen in northern Peru, and no connection had been made to the spectacular climatic effects, well known to that desert population. It is only through the written records of these effects (ship logs, missionaries, early explorers, civil archives, grain manifests, etc.) that *Quinn et al. (1987)* could document the probable occurrences of El Niño as far back as

1525. This compilation provides us with the baseline time series for verification of many proxy records, and suggests ways in which anecdotal evidence for climatic events can be extended even further back in time, e.g., with the help of Chinese scholars.

The most widely held notion of how ENSO works — as a dynamic, internal, oscillation of the Pacific ocean-atmosphere system — involves two critical elements: A positive feedback mechanism, in which ocean-atmosphere interactions create an unstable change of state that would be impossible with either medium alone, and a negative feedback, whereby the instability is "turned off" and the system returned to the previous state. A plethora of research gives us little doubt about the general outlines of the first mechanism, which occurs primarily in the west-central equatorial Pacific (*Philander, 1989*). The second mechanism (e.g., *Graham & White, 1988*) is much more controversial, as it relies on imperfect models and sparse observations. To this we must add the suggestions of some that external triggers are necessary, and may come from unexpected regions of the globe (e.g., *Barnett et al., 1988*), or from the interaction with other oscillatory phenomena, such as the intraseasonal oscillation (40-60 days), the Quasi-Biennial Oscillation (QBO — 26 months) or solar variations (11 years, 22 years, 80-90 years) (*Lau & Chan, 1988; van Loon & Labitzke, 1987; Anderson, 1990*).

The impacts of ENSO that are occurring in the 20th century give us clues to what we should look for in the paleoclimatic record, and where to find it. In the equatorial Pacific and along the eastern Pacific boundary, ENSO warms the surface water, raises sea levels, and affects biological productivity. Droughts occur in Indonesia and Australia, and the Asian Monsoon is thought to be affected in (yet) unpredictable ways. Torrential rains and coastal flooding occur in Ecuador and northern Peru, with droughts in the Andean Altiplano and the region of Suriname and NE Brasil. Altered jetstreams usually intensify the storminess over subtropical North and South America (*Ropelewski & Halpert, 1987*). As a result of these responses, we can expect to find changes in biological deposits, such as oceanic and lacustrian sediment varves (*Baumgartner & Christensen, 1985*), coral skeletons (*Shen et al., 1987*) and subtropical tree rings (*Michaelsen, 1990*); there will be variations in the deposition of evaporites, as well as the thickness and contents of ice cores (*Thompson et al., 1984*); and on even longer time scales we can see the erosive and depositional effects of El Niño-related flooding (*Wells, 1987; Rollins et al.*).

Beyond the disciplinary task of constructing reliable proxy chronologies, our challenge is to innovate new and more effective ways of analyzing this kind of data. In the context of ENSO, for example, the attempt to verify proxy time series against the record of known events (e.g., *Quinn et al., 1987*) is only the first step, and we can expect difficulties in establishing 1:1 correspondence between them. Additionally, we should try to relate the <u>statistical structure</u> of the proxy series to that of the verification data set, and look for evidence of prior, significant changes in that structure. This is the problem of stationarity, and one that promises to reveal much about the way the ocean-atmosphere climate system behaves.

References

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van Loon, H. and K. Labitzke, The Southern Oscillation. Part V: The anomalies in the lower stratosphere of the northern hemisphere in winter and a comparison with the Quasi-Biennial Oscillation, *Mon. Wea. Rev., 115*, 357-369, 1987.

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Precipitation patterns

A similar technique was applied to the precipitation data. As would be expected, the tropics contain the strongest, most spatially coherent and temporally consistent signals. From JJA(0)-MAM(+1), nearly all individual event anomalies are in the direction of the composite values.

A map illustrating the regions for JJA(0) is shown in Fig. 5, and the normalized seasonal time series is given in Fig. 6. Regarding the strength and reliability of the ENSO signals, in some regions it was found to be too unreliable for the occurrence of a particular regional anomaly pattern to be a useful ENSO predictor. I consider that at least two-thirds of the events should have the expected (composite) value. In terms of signal strength, typically half of the events are associated with seasonal anomalies exceeding half a standard deviation from the mean (one would expect 30% of randomly selected values to exceed this threshold). However, in some regions, the value is close to 90%.

A "global" index was formed in the same manner as described for the temperature. The time series for JJA(0) is given in Fig. 7, and shows that, as for temperature, averaging the values from several global regions yields a clearer signal, and hence reduces uncertainty associated with event-to-event variability in the climate record.

2. Summary

The reliability and strength of regional seasonal temperature and precipitation anomalies associated with ENSO extremes is examined, by looking at a global index of the expected regional responses (based on the composite mean). The anomaly pattern associated with ENSO is found to be quite unique in the climate record.

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Fig. 1 WARM-COLD ENSO COMPOSITE - DJF YEAR+1

MEAN TEMPERATURE

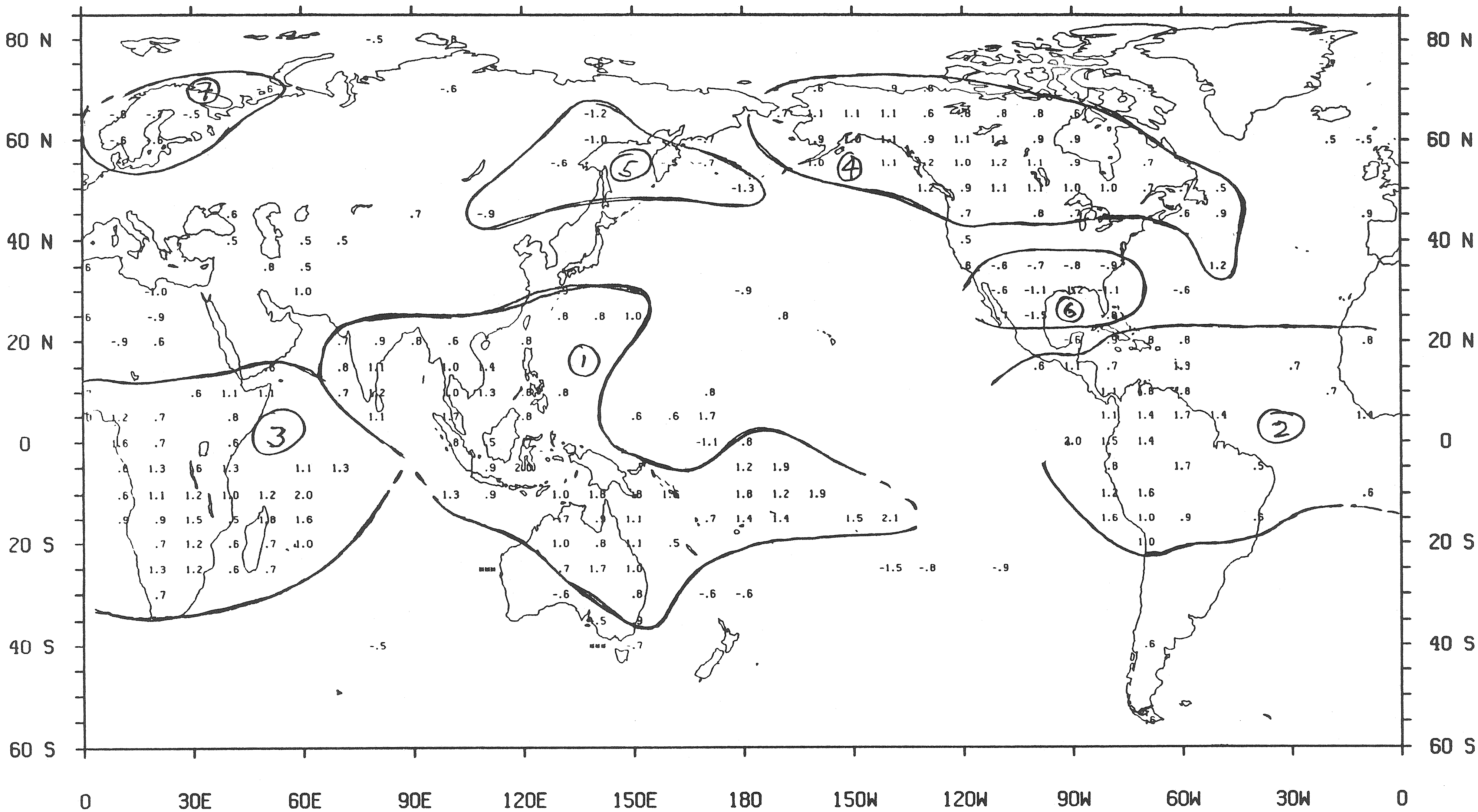
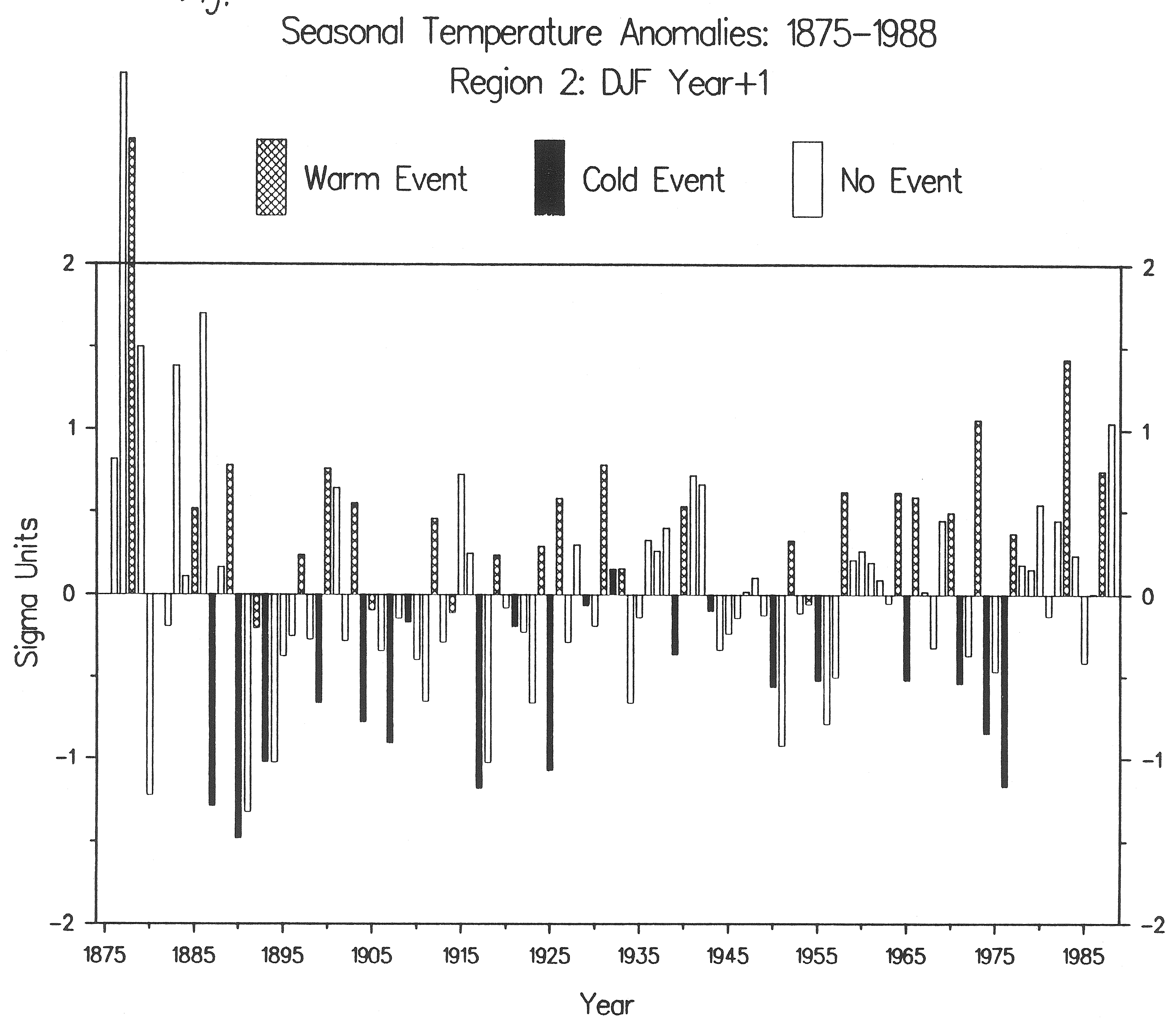
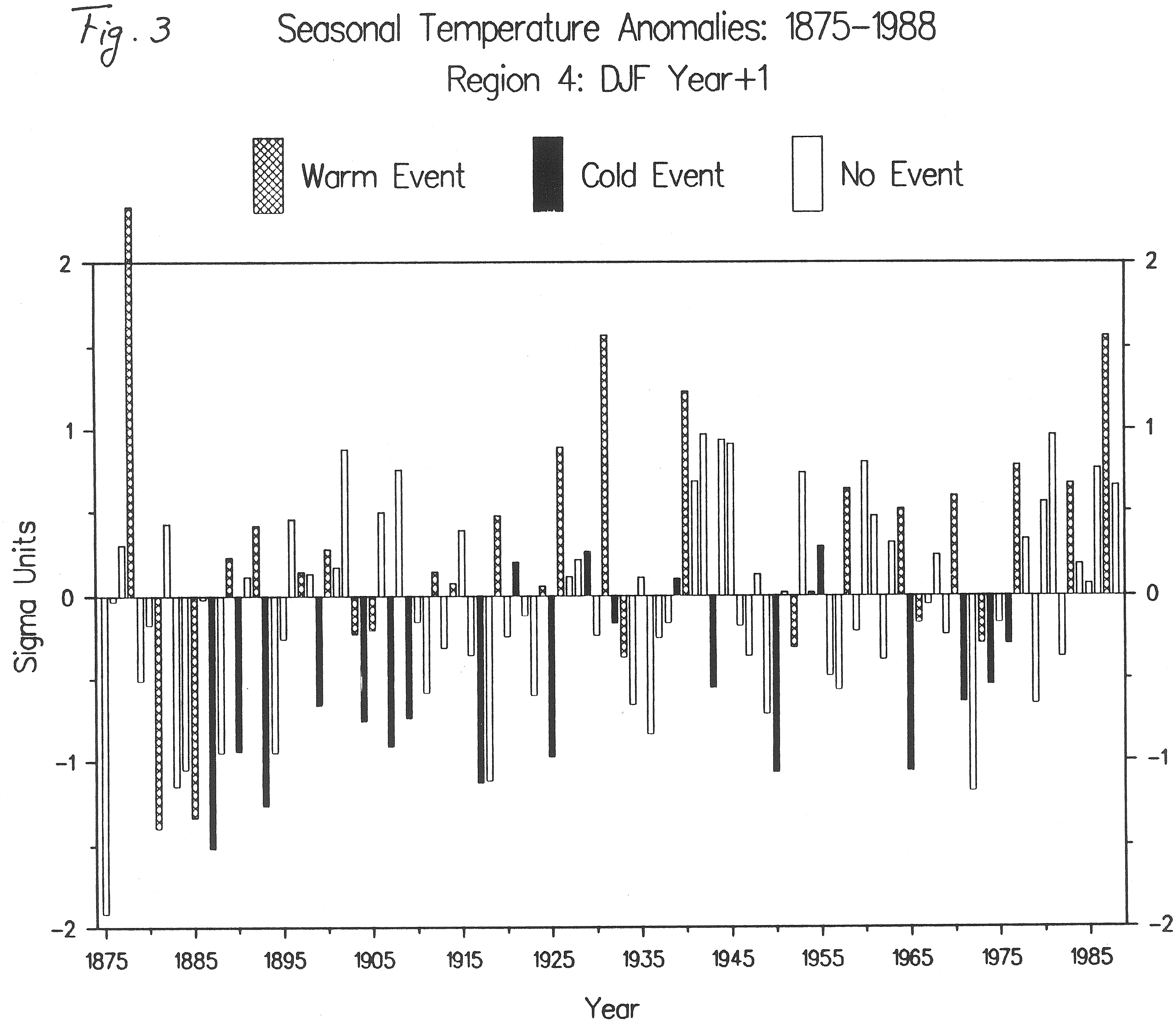


Fig. 2



Seasonal Temperature Anomalies: 1875–1988
Region 2: DJF Year+1
Warm Event
Cold Event
No Event
Sigma Units
2
1
0
−1
−2
1875
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
Year

Fig. 3



Seasonal Temperature Anomalies: 1875–1988
Region 4: DJF Year+1
Warm Event
Cold Event
No Event
Sigma Units
2
1
0
−1
−2
1875
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
Year

Fig. 5 WARM-COLD ENSO COMPOSITE - JJA YEAR Ø

TOTAL Precipitation

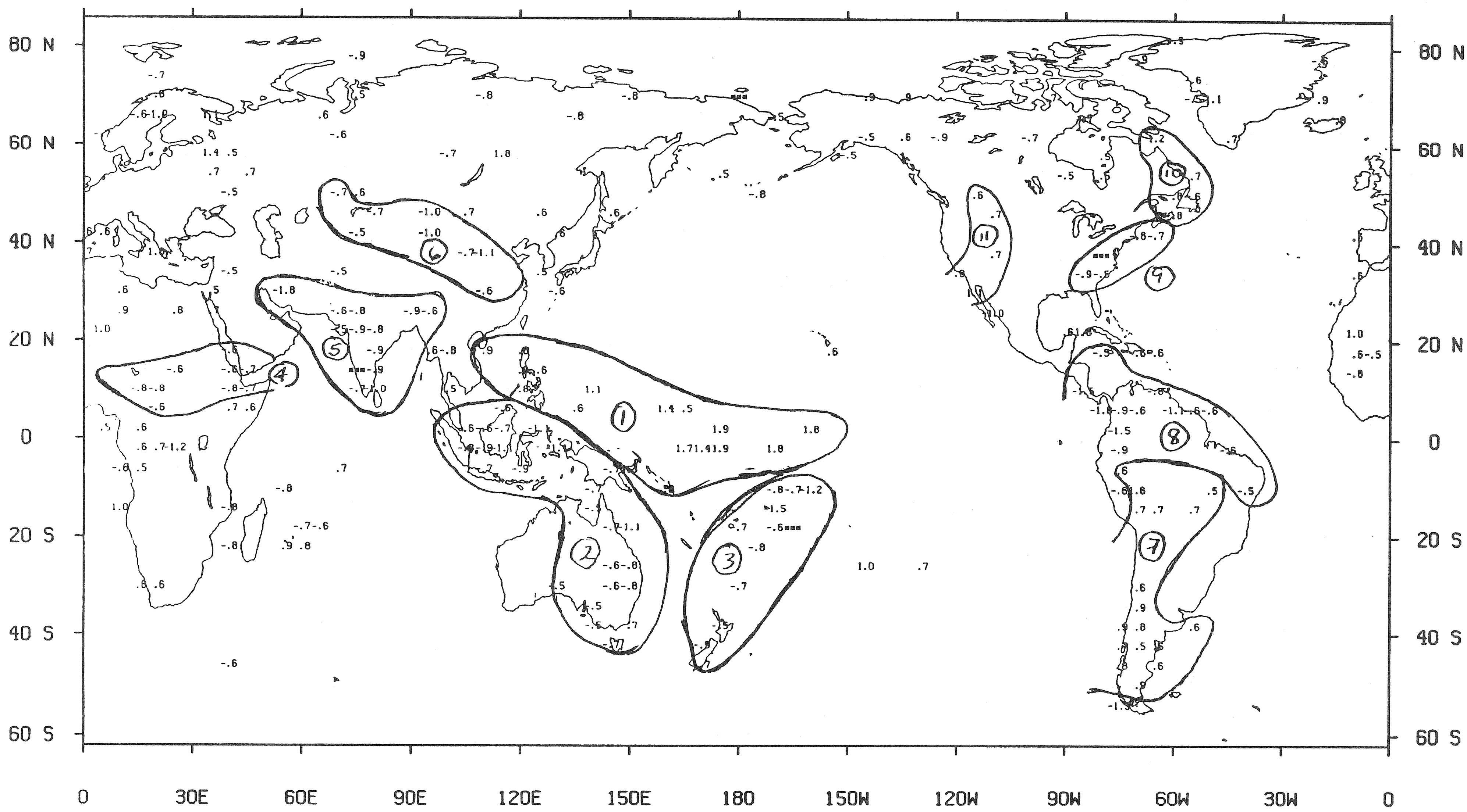


Fig. 6

Seasonal Precipitation Anomalies: 1875–1989

Region 1: JJA Year 0

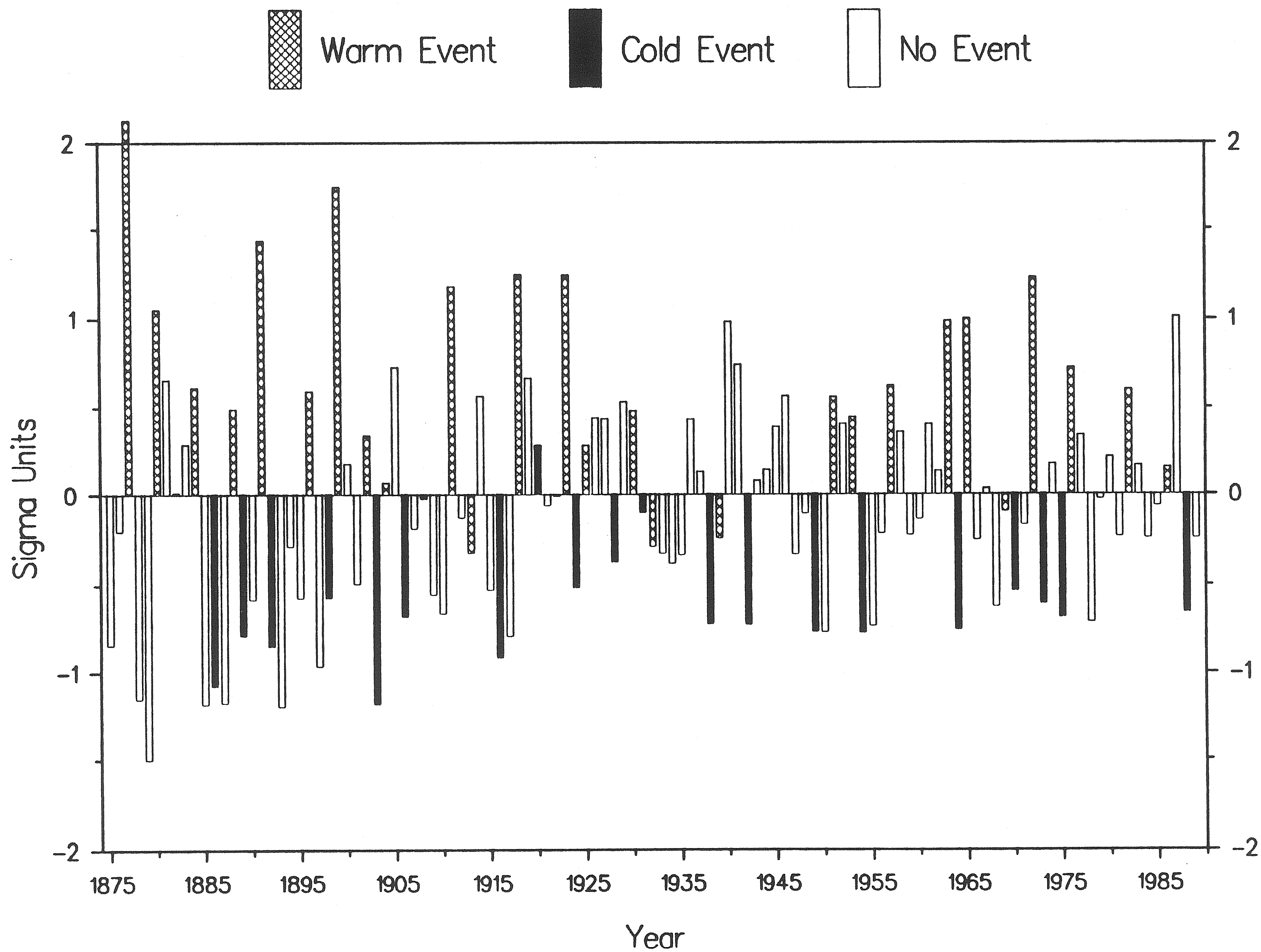
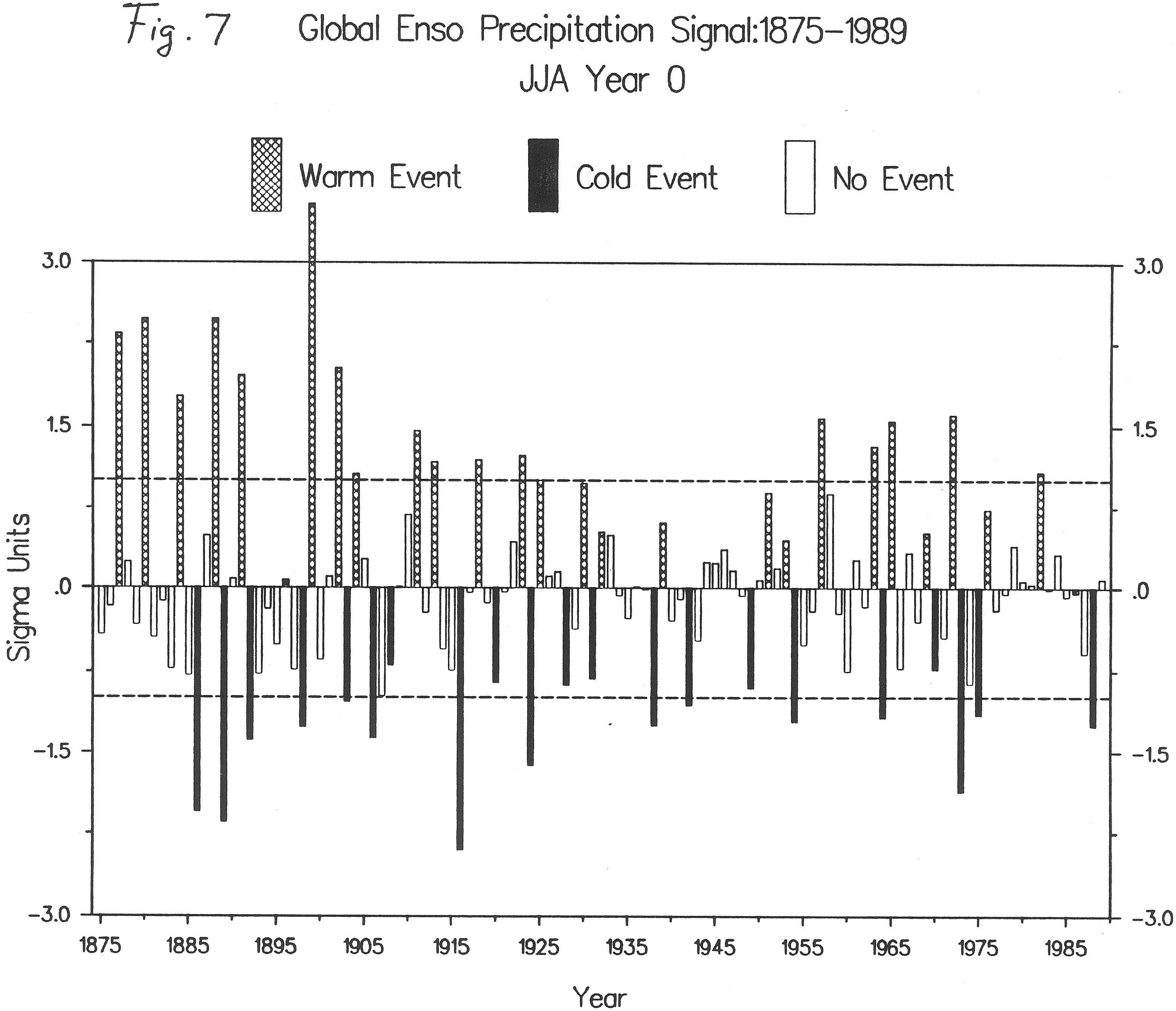


Fig. 7



Global Enso Precipitation Signal:1875–1989
JJA Year 0
Warm Event
Cold Event
No Event
3.0
1.5
.0
-1.5
-3.0
Sigma Units
1875
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
Year

A Preliminary Record of Southern Oscillation-Related Activity Extending about 1368 Years into the Past

Extended Abstract

William H. Quinn

College of Oceanography

Oregon State University

Corvallis, Oregon 97331-5503

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A Preliminary Record of Southern Oscillation-Related Activity Extending about 1368 Years into the Past

ABSTRACT

The quest to obtain a long record on Southern Oscillation (SO)-related climatic activity has for several years been concentrated on the El Niño (Quinn, 1987) which is considered to be a regional manifestation of the recurring large-scale SO-related ocean-atmosphere fluctuation (ENSO) that has been primarily noted over the lower latitudes of the Indo-Pacific area. The region directly affected by the El Niño is southwestern Ecuador, northwestern Peru and their coastal waters. By referring to this regional feature, we were able to obtain a record of its recurrence over a period of about 465 years from the various types of historical records and data available. Figures 1 and 2 (from Quinn and Neal, 1990) show the various El Niño occurrences and strengths which are documented in the 1990 report.

The next step was to find a way to extend this record of SO-related activity in time. This called for a reexamination of the various aspects of the parent large-scale feature. The SO as mapped by Berlage (1957) is shown in Figure 3. It shows how simultaneous deviations of mean annual pressures from their long-term average have a tendency to be of one sign over the tropical Indian Ocean and neighboring continental areas and the opposite sign over most of the tropical Pacific. Bjerknes (1969) also noted the definite tendency for opposite phases in pressure anomalies over the Indian Ocean and most of the tropical Pacific, with a nodal line in the pressure oscillation located over the western tropical Pacific near 165°E. Climatic authorities have at times likened the ocean-atmosphere fluctuations over this low latitude region extending from East Africa to South America to the actions of a "see-saw" with regard to the back and forth shift in values of some of the atmospheric and oceanic variables involved. From our studies of changes taking place on the large-scale we find, in general, that the low index phase of the SO relates on the east side of the "see-saw" to the northeast Brazil drought, El Niño, anomalously heavy subtropical Chilean rainfall, and anomalously heavy equatorial Pacific rainfall; whereas, on the west side it relates to the east monsoon drought over Indonesia, deficient summer monsoon rainfall over India, and a weak Nile flood. The high index phase of the SO relates, in general, on the east side of the "see-saw" to heavy northeast Brazil rainfall, cool anti-El Niño conditions over the northwestern South American coastal region and its adjacent ocean waters, anomalously low subtropical Chilean rainfall, and an equatorial Pacific dry zone that extends far to the west; whereas, on the west side it relates to anomalously heavy east monsoon rainfall over Indonesia, anomalously heavy summer monsoon rainfall over India, and an anomalously large supply of water entering the Nile River system from its Ethiopian source region during the summer monsoon season. The works of Rasmusson and Carpenter (1983) and Khandekar and Neralla (1984) further substantiate the associations between the two ocean areas by showing the relationship between sea surface temperatures in the equatorial Pacific and the summer monsoon rainfall over India.

As early as 1908 it was stated in the Imperial Gazetteer of India (volume 1, p. 127): "...it is now fully established that years of drought in western or northwestern India are almost invariably years of low Nile flood.

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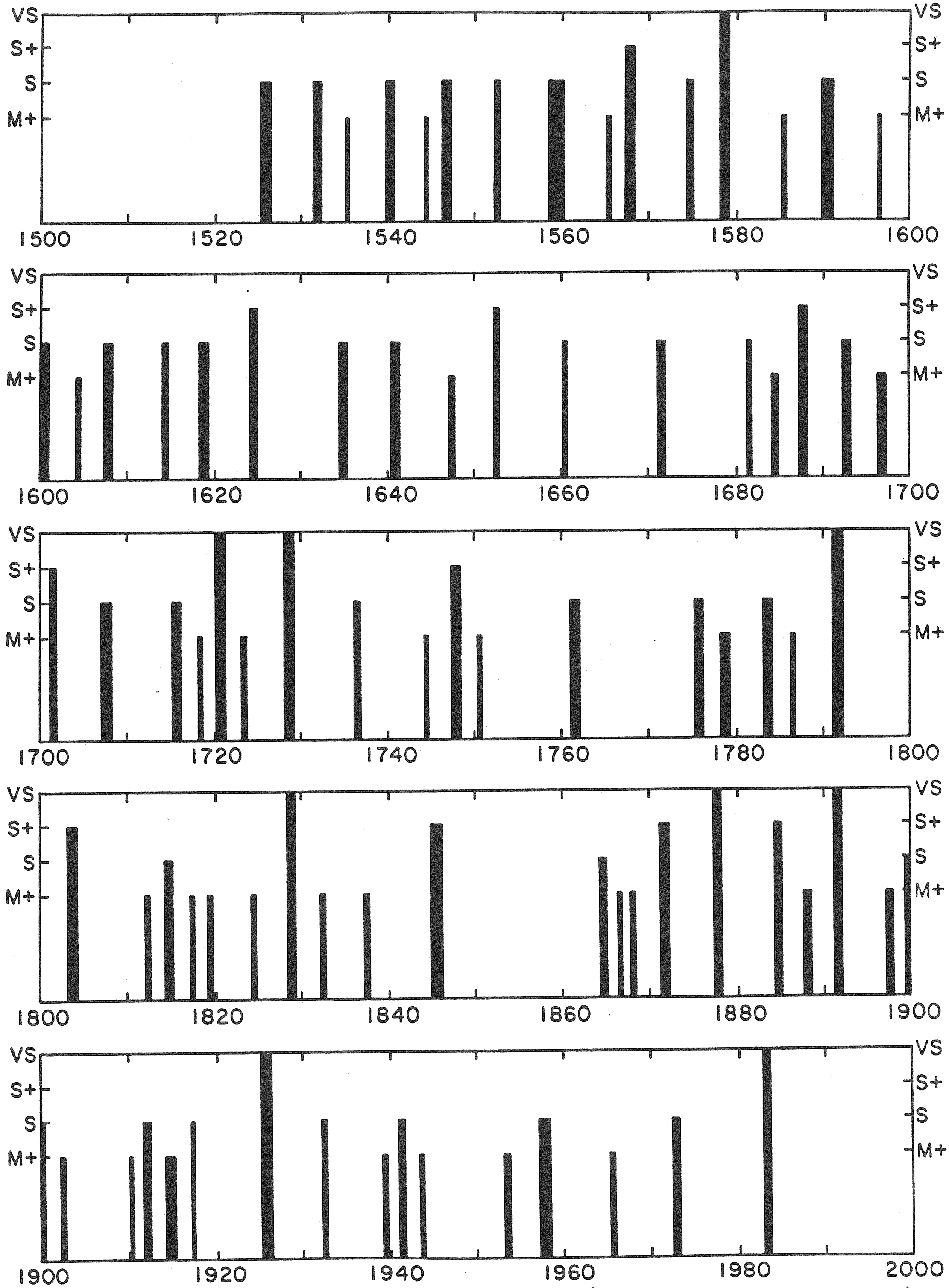

Figure 2. A graphic presentation of the 1525-1983 record of stronger events. Events shown here by century are limited to the M+ - VS intensity levels of entries in Table 1 of the Quinn and Neal (1990) text.

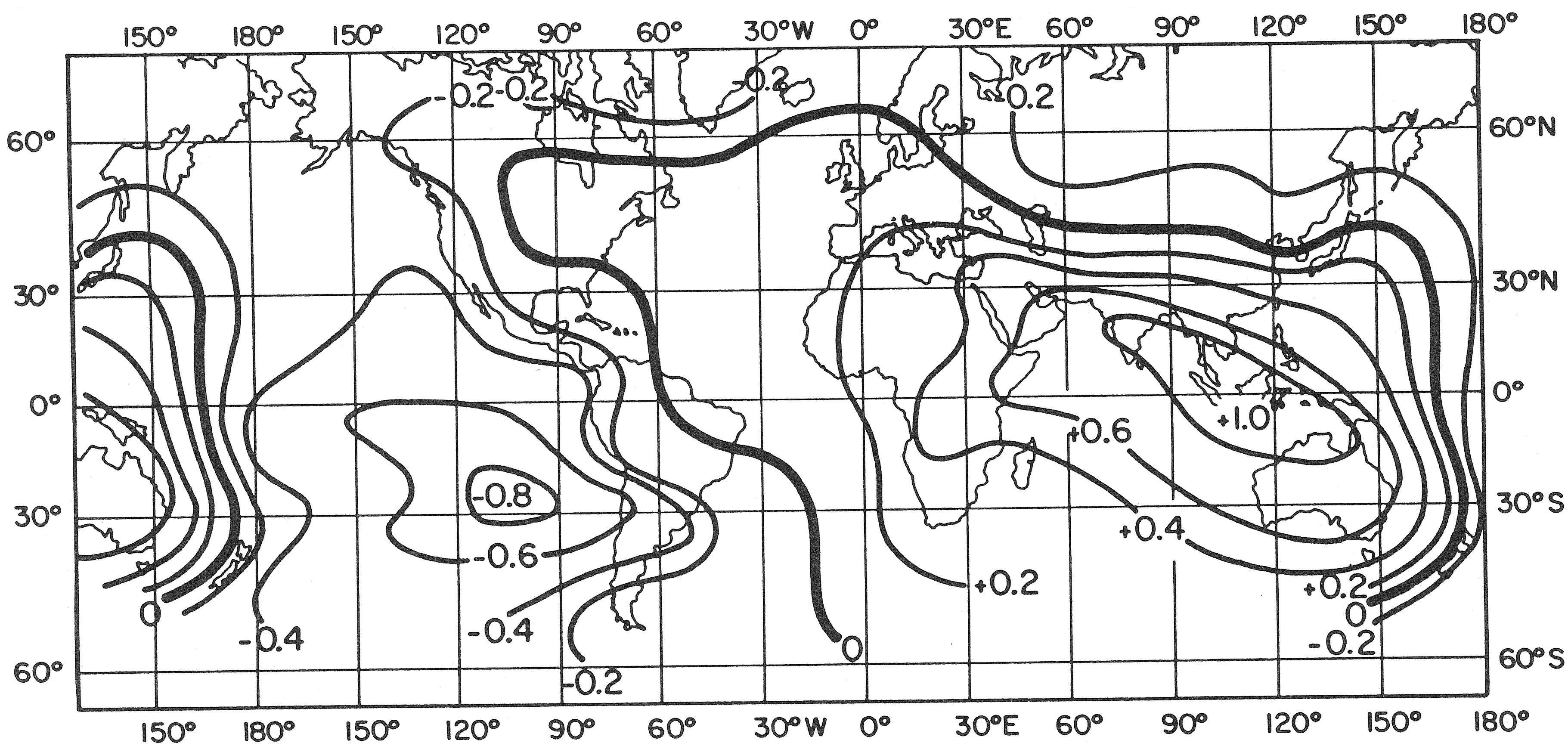

Figure 3. Walker's Southern Oscillation as shown in Berlage (1957). This map shows the worldwide distribution of correlations of annual pressure anomalies with simultaneous pressure anomalies in Djakarta, Indonesia.

Table 1. Large-scale ENSO events and several regional manifestations thereof that occurred in association with low index phases of the SO between 1824 and 1953. (Details on contents of this table are in the text.)

ENSO		El Niño		E. Monsoon	Deficient India	Weak Nile Floods				Low SOI
Yrs	Str	Yrs	Str	Drought	Summer Monsoon	Yrs	M-L	H-L	M'-F	
1824-25	S	1824	M+	ND	1824-25	1824 1825	1.16 1.12	ND ND	ND ND	ND ND
1827-28	S	1828	VS	ND	1828	1828	.47	.52	ND	ND
1830	M	-		ND	-	1830	.54	1.31	ND	ND
1832-33	S	1832	M+	1833	1832-33	1833	1.18	1.07	ND	ND
1835	W	-		1835	-	1835 1836	1.00 .71	1.21 .92	ND ND	ND ND
1837-38	S	1837	M+	1838	1837-38	1837 1838 1839	1.12 .49 .91	1.33 .70 1.12	ND ND ND	ND ND ND
1844-46	VS	1844-46	M/S+	1844-45	1844	1845	.73	1.23	ND	1845-46
1848	W	-		-	1848	-			ND	1848
1850	M+	1850	M	1850	1850	1850	.40	1.24	ND	1850
1852-53	M+	1852	M	1853	1853	1852	.54	1.47	ND	1852-53
1854-55	M+	1854	M	1855	1855	1855	.69	1.39	ND	1854-55
1857-59	M+	1857-58	M	1857	-	1857 1858 1859	.38 .47 .55	1.29 1.38 1.46	ND ND ND	1857-59
1860	M	1860	M	-	1860	-			ND	-
1864	S	1864	S	1864	1864	1864	.93	2.22	ND	1864
1866	W	1866	M+	-	1866	-			ND	1866
L1867-69	S	L1867-68	M+	-	1868-69	1868	1.02	2.60	ND	L1867-E69
1871	W	1871	S+	-	-	-			-	1871
1873-74	M+	E1874	M	1873	1873 SBM	1873	.76	1.49	1170	1873-E74
L1876-78	VS	1877-78	VS	1877	1877,1876 SBM	1877	1.67	3.75	2260	L1876-E78
1880-81	M	1880	M	1881	1880 SBM	1880 1881	.44 -	2.38	510 580	1880-81
1882-83	W	-		1883	-	1882	.52	1.27	1140	-
1884-85	M+	1884	S+	1884-85	-	1884 1885	.11 -	.86	1170 410	1884-85
1887-E89	S	1887-89	M-/M+	1888	1888 SBM	1886 1888 1889	.20 1.28 -	.95 2.59	640 1930 190	L1887-E89
1891	S	1891	VS	1891	1891 SBM	1891	-		60	1891
1896-97	M+	1897	M+	1896	1896 SBM	1897	.22	1.42	870	1896-97
1899-1900	S	1899-1900	S	-	1899	1899 1900	1.75 .62	2.41 1.28	1062 -	1899-1900
L1901-02	M+	1902	M+	1902	1901,1902 SBM	1901 1902	.54 1.30	1.20 1.96	- 892	L1901-02
1904-05	S	1904-05	M-	1905	1905,1904 SBM	1904 1905	1.10 1.14	.95 .99	172 742	L1904-05
1907	M	1907	M	-	1907 SBM	1907	1.30	1.13	1212	1907
1911-12	S	1911-12	S	-	1911,1912 SBM	1911 1912	.26 .81	.81 1.36	- 552	1911-12
L1913-15	S	1914-15	M+	1913-14	1913,1915 SBM	1913 1914 1915	2.15 .22 1.18	2.70 .77 1.73	2635 - 1232	L1913-E15
1918-20	S	1918-19	M	1918-19	1918,1920	1918 1919 1920 1921	1.08 .64 .59 .44	2.23 1.79 1.74 1.59	1022 262 162 282	1918-E20
1923	W	1923	M	1923	1923 SBM	-			-	1923
1925-26	S	1925-26	VS	1925-26	1925 SBM	1925 1926	1.15 .55	1.54 .94	1042 -	1925-26
1927-M28	W	1927	W	-	1928 SBM	1927 1928	.69 .42	.50 .23	572 252	L1927-M28
L1929-E31	M+	1930-31	M	1929	1930 SBM	1930 1931	.24 .19	.92 .87	562 112	L1929-E31
1932	M	1932	S	1932	1932 SBM	1933	.40	.30	272	1932
1939	M	1939	M+	-	1939 SBM	1939	.63	1.49	1072	1939-41
1940-41	VS	L1940-41	S	1940-41	1941	1940 1941	.68 1.56	1.54 2.42	1195 1796	see above
1943-44	M+	1943	M+	1944	-	1943 1944	- .31	.86	162 875	1943-44
1946	W	-		1945-46	-	1945	.79	1.34	422	1946
1948-E49	W	1948	W	-	-	1948 1949	.33 .28	.77 .72	262 252	1948-E49
1951-E52	M+	1951	M-	-	1951,1952 SBM	1951 1952	.24 -	.61	1012 682	1951-E52
1953	M+	1953	M+	1953	-	-			-	1953

Table 2. Years when low summer maximum levels of the Nile River at Cairo occurred, and evaluations of these levels with respect to long-term mean maximum values and prior year high summer maximum levels over the period A.D. 622-1522, as obtained from Toussoun (1925). (See text for details.)

Year	M-L	Deg.	H-L	Deg.
629	1.12	3	1.64	4
632	.65	2	.60	1
642	.58	2	1.12	2
650	1.57	4	1.90	4
662	.27	1	.72	1
678	.60	2	.61	1
683	.38	1	.58	1
687	1.14	3	1.05	2
688	1.08	3	.99	2
694	1.57	4	1.59	4
701	.96	3	1.49	3
704	.83	2	1.18	2
713	1.21	3	1.28	3
722	.45	1	1.07	2
726	.51	1	1.16	2
733	.63	2	1.11	2
735	.69	2	1.17	2
737	.45	1	.88	2
756	.69	2	1.23	2
759	.31	1	.60	1
762	.29	1	.67	1
764	.72	2	1.10	2
769	.58	2	.81	2
770	.58	2	.81	2
776	.58	2	1.01	2
780	.47	1	.99	2
782	.83	2	1.35	3
788	.55	2	.92	2
789	.54	1	.91	2
791	.74	2	.76	1
796	.40	1	.78	1
797	.60	2	.98	2
799	.63	2	.84	2
802	.83	2	1.14	2
803	1.12	3	1.43	3
812	1.05	3	1.49	3
817	.74	2	1.67	4
828	.33	1	.56	1
830	1.27	3	1.50	3
832	1.07	3	1.39	3
833	.66	2	.98	2
837	.75	2	.73	1
841	1.38	4	1.58	4
842	1.38	4	1.58	4
848	.66	2	.82	2
851	.89	3	1.26	3
860	.21	1	.58	1
881	.89	3	1.27	3
888	.48	1	.85	2
895	.89	3	1.24	2
903	1.70	4	2.02	4
917	.26	1	.69	1
927	.89	3	1.37	3
931	.57	2	.99	2
939	.73	2	1.13	2
941	.48	1	.88	2
942	.48	1	.88	2
945	.39	1	1.09	2
948	.66	2	1.36	3
949	.78	2	1.48	3
964	.57	2	.99	2
966	.78	2	.82	2
967	1.89	4	1.93	4
977	.24	1	.60	1
982	.60	2	.58	1
989	.37	1	.47	1
1007	.84	2	1.15	2
1008	.48	1	.79	1
1022	.72	2	1.32	3
1028	.31	1	.44	1
1036	.65	2	.79	1
1057	.56	1	.66	1
1066	.72	2	.75	1
1072	.43	1	.39	1
1085	.65	2	.75	1
1122	.27	1	.67	1
1124	.26	1	.54	1
1132	.22	1	.42	1
1142	.22	1	.47	1
1144	2.37	4	2.57	4
1160	.91	3	1.22	2
1200	1.99	4	2.21	4
1201	.52	1	.74	1
1211	.64	2	.64	1
1219	.77	2	1.05	2
1228	.26	1	.50	1
1231	.31	1	.55	1
1234	.28	1	.57	1
1245	.85	2	1.16	2
1290	.47	1	.74	1
1294	.67	2	.84	2
1297	.45	1	.69	1
1298	.63	2	.87	2
1310	.31	1	.55	1
1314	.24	1	.50	1
1321	.26	1	.55	1
1326	.32	1	.54	1
1331	.29	1	.40	1
1334	.29	1	.42	1
1339	.42	1	.55	1
1348	.28	1	.47	1
1362	.24	1	2.41	4
1363	.22	1	2.39	4
1370	.33	1	.67	1
1374	.85	2	.75	1
1380	.42	1	.56	1
1385	.30	1	.68	1
1389	.42	1	.77	1
1398	.33	1	.54	1
1404	.59	2	.80	2
1424	.47	1	.79	1
1427	.60	2	.79	1
1450	1.16	3	1.32	3
1461	.39	1	.47	1
1474	.76	2	.75	1
1484	.38	1	.80	2
1490	.52	1	ND	
1492	.44	1	ND	
1497	.89	3	ND	
1510	.39	1	.36	1
1518	.29	1	.65	1
1520	.30	1	.30	1

events, with drier than normal conditions in the east and north. Fiji is also usually dry during El Niño events (Dennet et al., 1978).

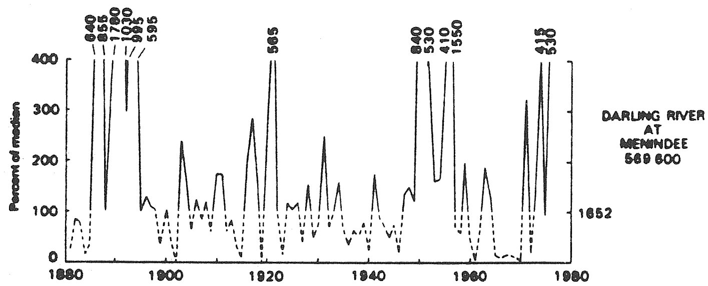

Figure 1: Annual streamflow (percent of median) in the Darling River. Median flow in million cubic metres shown on righthand axis

The period of documentary data

New South Wales, later to become one of the states of the Commonwealth of Australia, was colonised by Britain in 1788. Nicholls (1988a) examined reports of the governors of the colony to the colonial secretary of the British Government in London for references to drought from 1788 to 1841. Droughts were mentioned in the El Niño years of 1791, 1804, 1814, 1817, 1819, 1824, 1828, and 1837. Droughts were also mentioned in 1796, 1798, and 1810, none of which were El Niño years according to Quinn et al. (1987). The moderate El Niño events of 1821 and 1832 were not mentioned as severe droughts in the governors' correspondence. Russell (1877) lists both these years, however, as drought years. On the other hand, he does <u>not</u> indicate that severe droughts occurred in 1796 and 1798.

Russell (1877) lists droughts and floods in the colony up to 1875. He lists droughts in the El Niño years of 1845, 1850, 1854, 1857, 1864, 1866, and 1868. Droughts also occurred in 1861-1863 which were not El Niño years. El Niño events were also noted by Quinn et al. (1987) for the years 1860, 1871, and 1874. None of these were drought years according to Russell (1877), although Russell (1896) notes that 1871 and 1874 were dry. He also notes that 1877, another major El Niño year, was a severe drought year.

So, between 1788 and 1879, nearly all El Niño events were accompanied by Australian droughts, and vice-versa. This association confirms that found on the more recent quantitative rainfall data (e.g. Ropelewski and Halpert, 1987). Similar studies do not appear to have been done for New Zealand and Fiji.

Australia before British colonisation

Is there evidence that ENSO was affecting Australian rainfall before 1778? There are no records, either quantitative or documentary, from before this date. Nicholls (1989) speculated that the adaptations of Australian wildlife to highly variable rainfall was evidence that ENSO had been affecting Australia for at least thousands of years. Nicholls (1988b) demonstrated that ENSO amplifies the interannual variability of rainfall in areas it affects - such areas really are lands "of droughts and flooding rains". If ENSO has been doing this for a long time, the vegetation and wildlife should be adapted to this high variability. In fact much of Australia's native fauna <u>is</u> adapted to cope with highly variable rainfall (Nicholls, 1989), as is its native vegetation. This somewhat circular argument suggests, therefore, that ENSO has been affecting Australia's rainfall for a very long time. It would be useful to examine paleoclimatic data to determine if there is other evidence of ENSO's effects on Australian rainfall.

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Several decades of monthly average streamflow, beginning as early as the late 1800's, are available. Much of the material in this talk is taken from a study of the variable from about 40 such streams (Cayan and Peterson, 1989). Records such as these were used to examine the influence of atmospheric circulation on streamflow over western North America and Hawaii. In addition to a strong annual cycle in mean streamflow and its variance at most of the stations, there is also a distinct annual cycle in the autocorrelation of anomalies that is related to the interplay between the temperature and precipitation annual cycles. Of particular importance to these lag effects is the well-known role of water stored as snow pack, which controls the delay between peak precipitation and peak flow and also introduces persistence into the non-seasonal streamflow anomalies, with time scales from one month to over one year.

Winter (December through February) mean atmospheric circulation anomaly patterns over the North Pacific are significantly related to streamflow fluctuations over this network, with maximum correlations between winter sea level pressure and December-August streamflow ranging from 0.3 to about 0.6. For streams along the West Coast corridor, the circulation pattern associated with positive streamflow anomalies is low pressure (SLP) centered off the coast to the west or northwest, indicative of increased winter storms and an anomalous southwesterly wind component. For streams in the interior, positive streamflow anomalies are associated with a positive SLP anomaly stationed remotely over the central North Pacific, as well as negative but generally weaker SLP anomalies locally.

One important influence on streamflow variability is the strength of the Aleutian Low in winter. This is represented by the familiar PNA index and also by the "CNP", an index beginning in 1899 that is the average of the SLP anomaly south of the Aleutians and the western Gulf of Alaska. Relationships of PNA or CNP with streamflow in certain regions can be interpreted from the alternations in strength and position of the mean North Pacific storm track entering North America as well as changes in the trade winds over the subtropical North Pacific. Regions whose streamflow is best tuned to the PNA or CNP include coastal Alaska, the northwestern United States, and Hawaii, the latter two regions having the opposite sign anomaly as the former.

The "mature" winter phase (Rasmusson and Carpenter, 1982) of the El Niño /Southern Oscillation (ENSO) is associated with low pressure in the central North Pacific in winter. The Southern Oscillation index vs. streamflow anomaly correlation pattern is similar to that of CNP and PNA, but with two differences. In this analysis, the SOI correlation along the Alaskan coast is weaker than that with CNP and PNA, although Yarnal and Diaz (1986) reported significant correlations of coastal Alaskan precipitation with ENSO activity. The weakness of this relationship probably arises from the variability in the longitude of the North Pacific low, which can be seen from the broad loci of anomalous troughs accompanying strong El Niño during winter (Peterson *et al.*, 1986). A more westerly position of this trough favors the winter storm track moving into the Alaskan coast, while a more easterly position is associated with storms entering the West Coast farther south. Further insight into the types of Northern Hemisphere circulation patterns that appear with ENSO is provided by Fu *et al.*, (1986), and Livezey and Mo (1987), who suggest that the configuration of tropical Pacific heating may help to determine the pattern of extratropical response.

Interestingly, SOI is significantly related to precipitation and streamflow over the southwestern United States, while PNA and CNP are not. Streamflow anomalies in the Southwest from Southern California through Arizona and Southern Colorado tend to be positive (wet) while those in the Pacific Northwest are negative (dry) during the warm eastern tropical Pacific phase of ENSO (Redmond and Koch, personal communication). There is an important distinction between the results with streamflow and the results of a previous investigation of the relationship between ENSO and North American precipitation by Yarnal and Diaz (1986), and Ropelewski and Halpert (1986), who found a suggestion that the El Niño phase of ENSO was associated with lighter than average precipitation in the Pacific Northwest, but this tendency was not strong enough for them to consider it to be reliable. Part of

the reason for this weakness appears to be the wavering of timing of the light precipitation between fall and spring. However, in basins with higher elevations, streamflow is not as sensitive to these timing changes as is the precipitation, since snowmelt from the cumulative precipitation constitutes a significant portion of the streamflow. Heavy Southwest runoff appears to result from active low mid-latitude storms that tap subtropical Pacific moisture, which is often transported by the subtropical jet stream. This heightened activity occurs over several months from fall through spring, as discussed by Douglas and Englehart (1981), Ropelewski and Halpert (1986), and Andrade and Sellers, (1988). Increased precipitation in the Southwest occurs during fall through spring in the El Niño phase of the Southern Oscillation, which would contribute to above-normal streamflow. A simplified view of storm tracks and the associated broad scale streamflow anomaly pattern during the mature phase of ENSO is shown in the bottom panel of Fig. 1.

Not all basins in the West are well related to PNA/CNP or SOI. The SLP pattern most reliably correlated with anomalous precipitation and streamflow in California is an SLP anomaly centered to the northwest at about (40°N, 130°W). The winter 700 mb height teleconnection pattern centered at this origin (see Namias, 1981) shows a very similar circulation domain as the California SLP correlation pattern. In comparison to the central North Pacific teleconnection, the California pattern is more regionally confined, and very weakly related to anomalies in the Aleutian Low region. A similar comparison is found for the atmospheric circulation pattern and teleconnection (not shown) associated with streamflow anomalies along coastal British Columbia. This reinforces the lack of a statistical connection between streamflow in these regions and strong or weak atmospheric circulation in the central North Pacific.

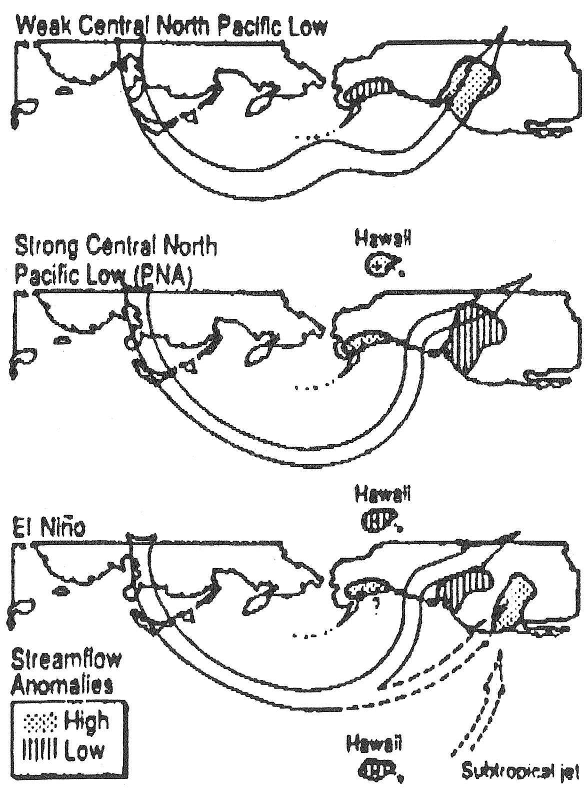

Fig. 1. Schematic of winter atmospheric flow and associated streamflow anomalies during weak central North Pacific low, strong central North Pacific low, and during northern hemisphere winter "mature" phase of El Niño.

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Model ENSO Cycles under late Pleistocene Conditions

Nicholas E. Graham
Scripps Institution of Oceanography
La Jolla, CA 92093

Simple coupled models of the tropical Pacific ocean-atmosphere system have been used extensively to study the nature of ENSO under the present climate regime. Recently, the application of one such model (that of Zebiak and Cane, 1987) has been extended to study potential changes in the character of the ENSO cycle that might occur under the climatic conditions projected to prevail under a greenhouse warming scenario. In these experiments, such background climatological fields as long-term mean SST, surface winds, and ocean currents are slowly varied in accord with the results from a transient CO_2 simulation using the Goddard Institute for Space Studies GCM (Hansen et al., 1988). The results suggest that the effect of increasing tropical Pacific SSTs is to produce significantly larger and more regular ENSO episodes. The changes in the other background fields act to moderate these effects. Of course, the relative simplicity of the coupled model and the uncertainties inherent in the GCM experiments limit the degree to which these results can be regarded as realistic. Nevertheless, some of the simulated effects rest on low order physical principles and the results highlight the sensitivity of the coupled tropical ocean-atmosphere system to changes in background conditions. This sensitivity suggests that GCM projections of possible future climate change need to account for tropical interactions that to date have been ignored in most experiments (a notable exception is described by Washington and Meehl, 1989).

In the course of the above mentioned experiments, one simulation was conducted in which background SSTs were decreased rather than increased. The model ENSO cycles were dramatically reduced. This result suggested an experiment in which background SSTs from the late Pleistocene (approximately 18,000 years BP) taken from the CLIMAP project estimates were used in the coupled model. The results from this experiment will be described.

COUPLED GCM SIMULATIONS OF ENSO: IMPLICATIONS FOR ENSO IN THE PALEOCLIMATIC RECORD [1]

Gerald A. Meehl
National Center for Atmospheric Research [2]
Boulder, Colorado 80307-3000

Recently, global coupled ocean-atmosphere general circulation models (GCMs) have been shown to be capable of internally generating some aspects of ENSO phenomena (Sperber et al., 1987; Philander et al., 1989; Meehl, 1990). In these coarse-grid models, only a subset of the processes thought to be taking place in observed ENSOs are simulated.

For example, Meehl (1990) shows that processes in the eastern Pacific associated with a modulation of the seasonal cycle there are present in ENSOs simulated in the National Center for Atmospheric Research (NCAR) global coupled GCM. However, in that model, features of ENSO in the western Pacific are not well-simulated. Anomalous warm water associated with the inception of ENSO in the eastern Pacific in the model appears off the South American coast in northern spring and moves toward the Dateline. During the mature phase of ENSO events in the coupled model (the season of December-January-February from the year of the inception of the event to the year following, commonly perceived as the time of year when teleconnections to the extratropics in the Northern Hemisphere are strongest), positive sea-surface temperature (SST) anomalies have become established near the Dateline. Associated with those SST anomalies in the equatorial Pacific are relatively low sea-level pressure (SLP) in the eastern Pacific and

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relatively high SLP over southern Asia and the western Pacific, the signal of the Southern Oscillation (compare Fig. 1b with observed SLP anomalies in Fig. 1a). In the extratropics, the teleconnections in the Northern Hemisphere resemble those during observed ENSO events. These include a deepened Aleutian low and a weak ridge over the western United States (Fig. 1a and b).

The coupled model at NCAR has been developed mainly to study climate sensitivity associated with an increase of carbon dioxide (CO_2). In the model with doubled CO_2 ($2\times CO_2$), ENSO continues to function *in the tropics* in much the same way as present but with mean SSTs in the tropical eastern Pacific higher by about 1°. There is also a somewhat larger amplitude fluctuation of SST anomalies from warm to cold phase.

However, the changed mean climate in the extratropics with the doubling of CO_2 is associated with notable altered extratropical teleconnection patterns in the $2\times CO_2$ El Niños compared to the present-day ($1\times CO_2$) El Niños. In particular, in Fig. 1c, the high northern latitudes are dominated by positive SLP anomalies compared to negative anomalies in the $1\times CO_2$ El Niños (Fig. 1b), while the high southern latitudes are characterized by low SLP anomalies where there were positive anomalies in the $1\times CO_2$ El Niños. Also the weak ridge over the western United States in the $1\times CO_2$ El Niños in Fig. 1b is a weak trough in the $2\times CO_2$ El Niños in Fig. 1c. These altered teleconnection patterns are thought to be associated with the modification of the mean climate basic state in the extratropics with the change in external forcing associated with the increase of CO_2.

This hypothesis is tested with a series of analog models ranging from an atmospheric GCM with idealized forcing, a linear barotropic model with idealized forcing, and a GCM coupled to a simple mixed layer ocean with prescribed SSTs

in the tropical eastern Pacific. All the analog models confirm that a change in the basic state in the extratropics associated with altered external forcing of the climate system causes a change in the extratropical teleconnections from ENSO events.

The implication for paleoclimate from these experiments is that a change in the climate basic state in the past (e.g., a change in orbital parameters and resulting adjustment of snow-ice extent and atmospheric circulation) could alter the response of the climate system in the extratropics to ENSO. This could be associated with an altered signature of ENSO in the paleoclimatic record in the extratropics compared to present.

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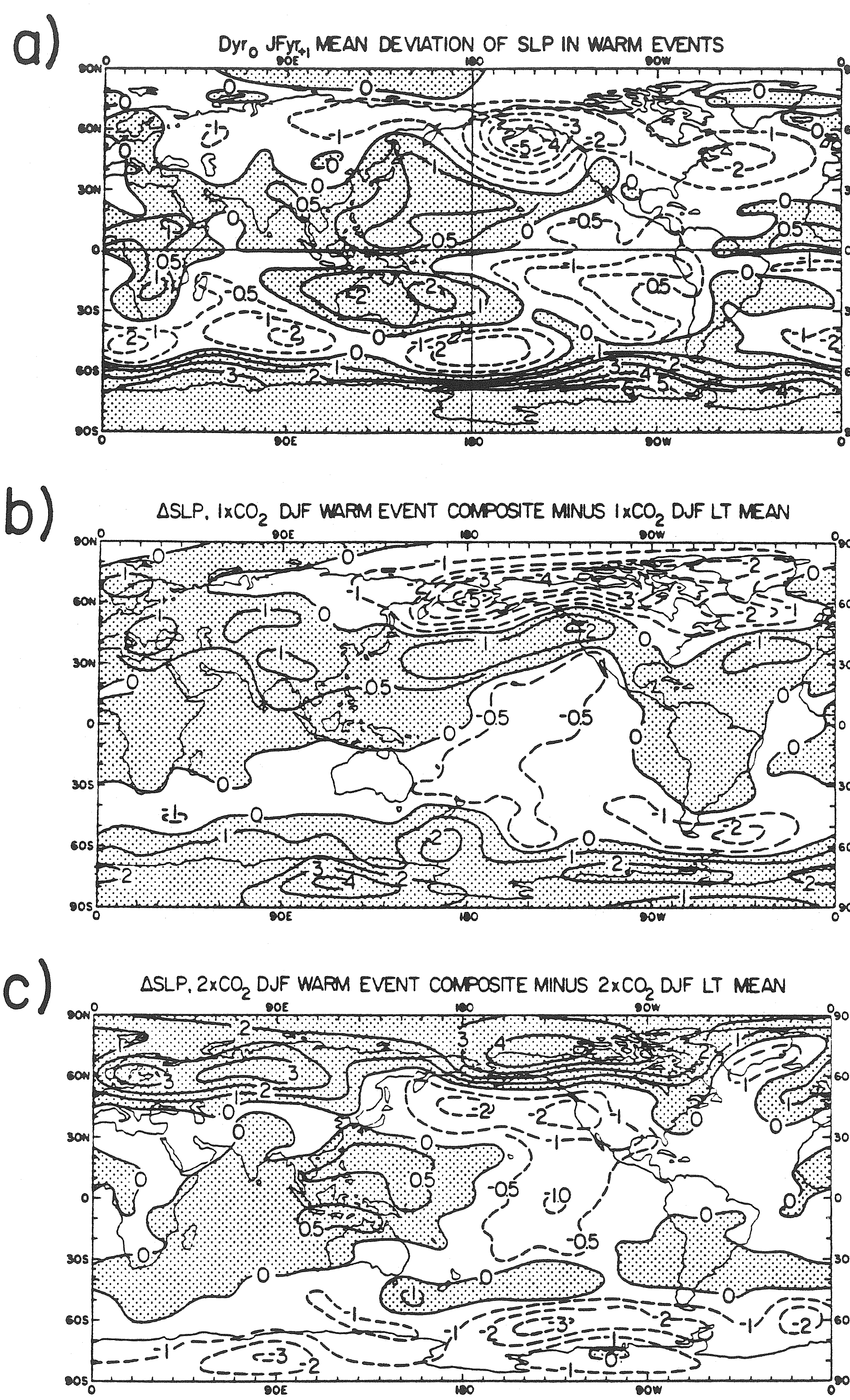

Fig. 1: **a) Observed SLP anomalies for DJF during mature phase of warm events minus long-term mean that does not include warm-event seasons from van Loon (1986); stippling indicates positive anomalies; b) SLP anomalies from the coupled model for present-day ($1\times CO_2$) warm-event composites minus $1\times CO_2$ long-term mean for DJF during mature phase; c) same as (b) except for $2\times CO_2$ warm-event composites minus $2\times CO_2$ long-term mean from the coupled model.**

Low-Frequency Changes in ENSO

David B. Enfield[1] and Luis Cid S.[2]

Although there are indications from numerical models that El Niño/Southern Oscillation (ENSO) may be an internal mode of the coupled Pacific Ocean/atmosphere system, sensitive to "climatic" background parameters, it has not yet been possible to find significant changes in ENSO variability between the Little Ice Age (LIA) and the present (Enfield, 1988). However, a number of authors have found evidence in anecdotal and proxy records for shorter, century scale variations in the return-interval statistics for El Niño episodes (Quinn et al., 1987, Enfield, 1988, Michaelsen, 1990, Anderson, 1990). These variations appear to coincide with changes in the amplitude of the 11-year cycle of solar activity, with longer return intervals (lesser El Niño frequency) corresponding to periods of enhance solar variability (Anderson, 1990). Unfortunately, none of the studies have been able to show conclusively that there is no relation to the LIA transition or that the apparent (centenary) nonstationarity in the return-interval data is significant. A classical time series approach fails in this situation because there are two few degrees of freedom in the data sets at the low frequencies involved. We have therefore re-examined the anecdotal compilation of Quinn et al. (QNA, 1987), using distribution fits and nonparametric testing procedures, to rigorously test for these nonstationarities.

We have stratified the return intervals for both all (A) El Niño vents (QNA Table2, 1803-1987) and for strong (S) events (QNA Table1, 1525-1983), according to two null hypotheses: 1) return intervals are stationary overall (no differences between first half and second half of a series); 2) the intervals are stationary between epochs of different solar variability (above median versus below median solar variability). For each subsample of data we use the maximum likelihood method to find the scale (τ) and shape (α) parameters for the Weibull (α,τ) distribution. We then use a modified Kolmogorov-Smirnov (KS) test for differences between the parameters of the various subsamples. At the 95% significance level, only the null hypothesis for high/low solar levels and strong El Niño events can be rejected. The corresponding hypothesis for all events rejects at the 90% level and overall stationarity cannot be rejected at any reasonable level. The Smirnov two-sample test and other indications are consistent with these findings. The significant results are: a) that El Niño is stationary with respect to long term climate changes, but b) that return intervals of strong events are significantly longer (14.4 years) during periods of energetic solar fluctuations than otherwise (8.8 years), and c) that events of all intensities exhibit the same tendency but less clearly (4.8 years vs. 3.6 years). The nonstationarity appears to be real, although we cannot conclude that the connection with solar activity is non-coincidental.

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1 NOAA/AOML, 4301 Rickenbacker Cswy, Miami FL 33149

2 Math. Dept., University of Concepcion, Concepcion, Chile

ENSO in the Paleoclimatic Record - an Overview

Vera Markgraf
Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado 80309

Analysis of global seasonal temperature and precipitation patterns related to ENSO events shows several regions of strong response, primarily in the tropics, but also at extratropical latitudes (Kiladis and Diaz, 1989). To address the question of long-term persistence of the ENSO signal in the past, or of intervals of extended occurrences of El Nino or La Nina events, paleoclimatic records may provide an answer.

At the time scales of thousands of years, however, other climatic forcing parameters, specifically the Milankovitch-type changes in seasonal insolation have to be considered as well. One approach to distinguish between ENSO and Milankovitch climate forcing is to compare precipitation and temperature patterns established for ENSO events with those predicted from Milankovitch paleoclimate model experiments. Using paleoclimatic model results by Kutzbach and Guetter (1986), the precipitation patterns for the full-glacial conditions (18,000 yr B.P.) show very little seasonal change, suggesting that the climate at that time was locked into a rather extreme mode that probably would not facilitate ENSO events. By 9000 yr B.P. on the other hand, seasonal differenes in precipitation patterns were substantial, and resembled in large measure some of the ENSO patterns, suggesting that ENSO events could very well have occurred. Past behavior of the Indian monsoon is an example to the point. Using a climate model based on a combination of Milankovitch insolation changes and volcanic events, Bryson (1989) could predict past shifts in wind direction over the Indian continent and hence monsoonal precipitation. Only during the Holocene did the modeled wind direction suggest monsoon rains in India, in agreement with paleoclimatic data from pollen records in Rajasthan (Sing et al., 1974; Swain et al., 1983). The Holocene itself was not homogeneous in terms of monsoon frequencies, both in the model results and in the paleoclimatic record. The early Holocene, between 10,000 and 6000 yr B.P. showed little variability in wind direction and paleoenvironments, whereas after 6000 yr B.P. and especially after 4000 yr B.P. the variability became extremely high. At that time the sequence of intervals of aridity, alternating with moister intervals resembles the ENSO pattern, with aridity during El Nino events and higher than normal monsoon during La Nina events. This implies that in this case, insolation changes alone could account for the paleoclimatic patterns, and although the existence of ENSO forcing is likely once the large-scale climate stage is set, it cannot be differentiated from the regional climate forcing.

Another approach that perhaps leads further in confirming past

Reconstructing the History of Interannual Climate Variability from Tropical and Subtropical Ice Core Records

By Lonnie G. Thompson

Byrd Polar Research Center, The Ohio State University,
Columbus, OH 43210 USA

Interannual variability in climate is a major feature of the climate system, particularly in subtropical and tropical regions. It is essential to know if the interannual variability signature in the climate record is affected by a change in the mean state of the climate system. This goal can be met only by analyzing long records of interannual climate variability throughout intervals in the past when climate was different from today (e.g., Little Ice Age, last glaciation). This task is especially important as man may be inadvertently altering the mean state of global climate.

Annual variations in the amount and chemical composition of precipitation accumulating on both polar and alpine (high elevation) glaciers produce laminations which allow precise dating of these stratigraphic sequences. The thickness of the annual lamination is related to the amount of accumulation while the physical and chemical constituents preserved therein (e.g., dust concentrations, isotopic abundances, ionic abundances) record local atmospheric conditions during deposition. A high resolution record from tropical ice cores reveals that the seasonal amplitude has varied substantially during the last 1000 years, doubling during the Little Ice Age (Thompson and Mosley-Thompson, 1989). Ice cores provide a direct archive of multiple parameters characterizing the terrestrial paleoatmosphere. Changes in atmospheric composition (both natural and anthropogenic), temperature, and precipitation regime are preserved, often at very high resolution, in carefully selected glaciers and ice caps. For the millenial time scale, only ice cores offer the opportunity to resolve interannual variability in the tropics on an annual basis. At present the longest such ice core is the 1500-year long record from the tropical Quelccaya ice cap (Thompson et al., 1984, 1985, 1986, 1988 and Thompson and Mosley-Thompson, 1987, 1989). However, recently recovered ice core records from the Qinghai-Tibetan Plateau (China) offer the potential of records through the last glacial cycle in the subtropics (Thompson et al., 1988, 1989, in press).

With the exception of the annual cycle, ENSO is the dominant global climate signal on time scales of a few months to a few years. It is associated with major dislocations of rainfall regimes in the tropics. Whereas the northern coastal desert regions of Peru experienced abnormally high precipitation, the southern highlands of Peru where Quelccaya is located experienced drought. Figure 1 illustrates variations in small diameter particle concentrations measured in samples from successive pits on the Quelccaya ice cap from 1975 to 1984. High particle concentrations are associated with the dry season from May to August. The dashed line represents the July snow surface, and hence the separation between pairs of these lines represents snow accumulation over the thermal year (July to subsequent June). Mass balance variations are given in meters of water-equivalent. The El Niño years of

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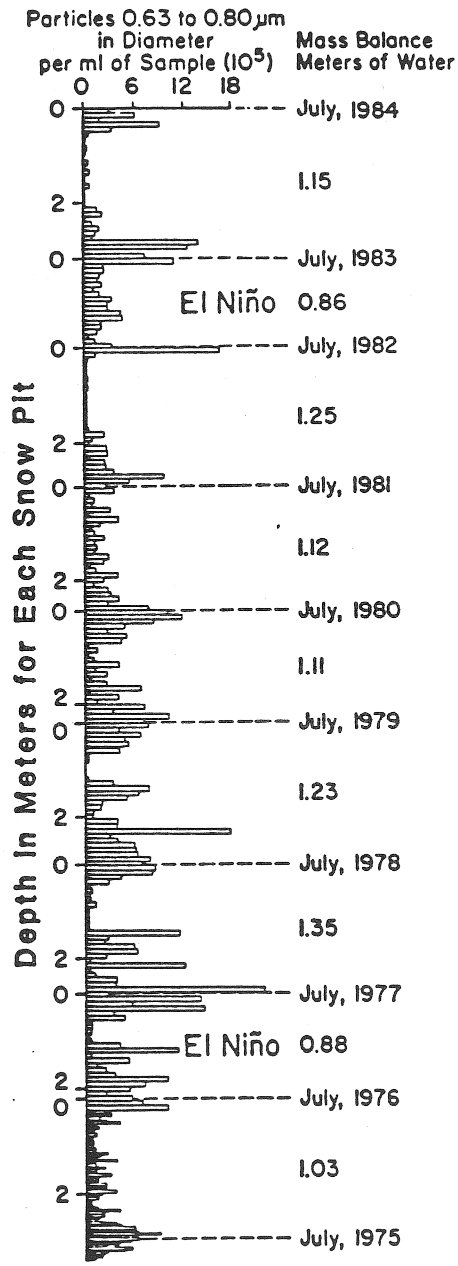
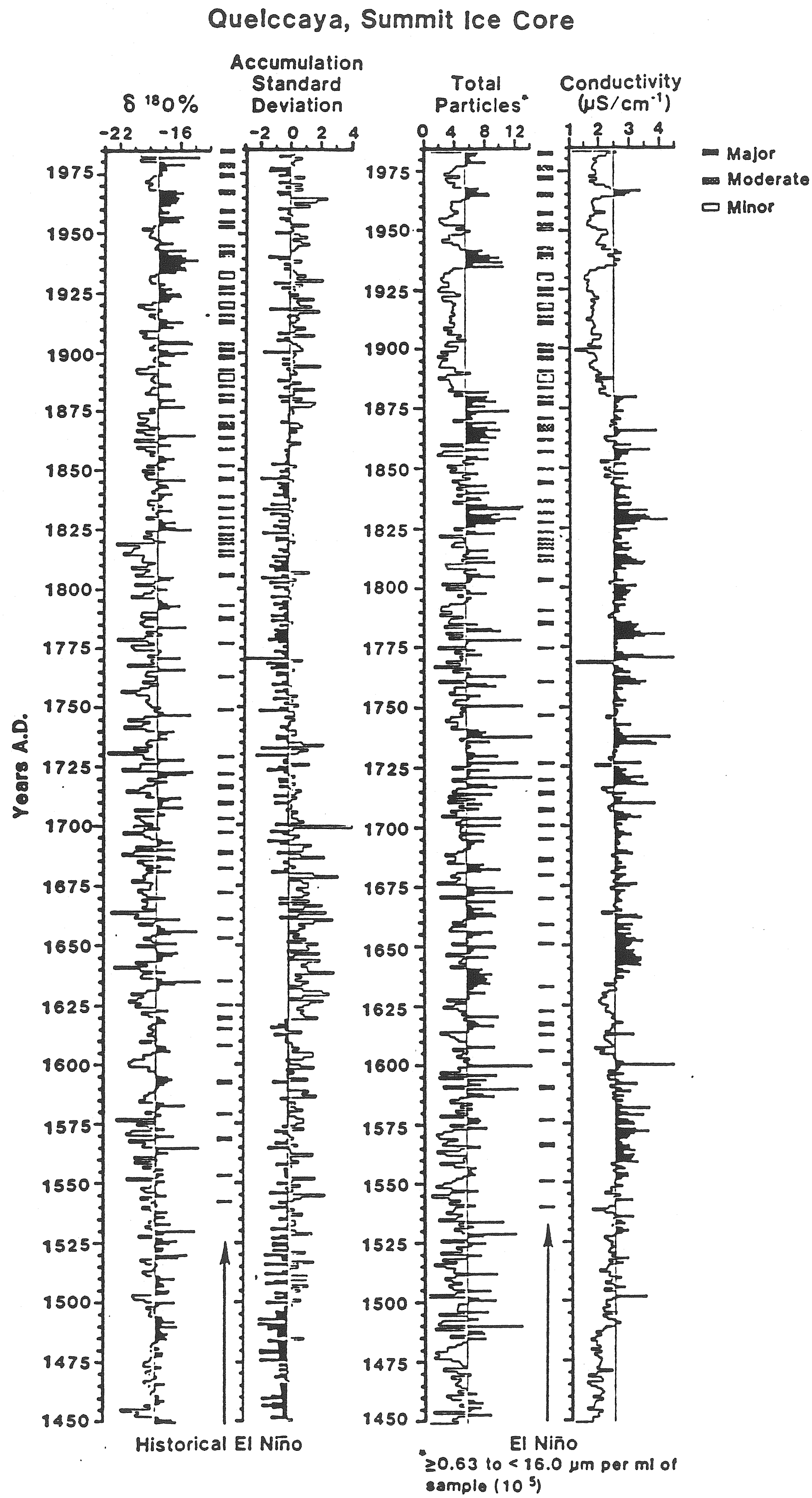
Figure 1. Small diameter particle concentrations measured in samples from successive pits on Quelccaya ice cap from 1975 to 1984. High particle concentrations are associated with the dry season from May to August. The dashed line represents the July snow surface, and hence the separation between pairs of these lines represents snow accumulation over the thermal year (July to subsequent June). Mass balance variations are given in meters of water equivalent. The El Niño years of 1976-77 and 1982-83 exhibit marked reductions in mass balance.

Figure 2. Annual variations in microparticle concentrations (total particles), conductivity, oxygen isotope ratios and accumulation as standard deviations for the last 500 years. The "Little Ice Age" from 1500 to 1880 A.D. stands out clearly and is characterized by increased soluble and insoluble dust and decreased (more negative) $\delta^{18}O$. The large dust event centered on 1600 A.D. was produced by the February 19-March 6, 1600 A.D. eruption of Huaynaputina, Peru. Also shown is the historical El Niño record from Quinn et al., 1987.

Quelccaya Ice Cap, Peru

Annual Variation of Microparticles and Precipitation




Quelccaya, Summit Ice Core
δ 18O%
Accumulation Standard Deviation
Total Particles*
Conductivity (μS/cm-1)
Major
Moderate
Minor
Years A.D.
Historical El Niño
El Niño
*≥0.63 to < 16.0 μm per ml of sample (10 5)

A COMPARISON OF PROXY RECORDS OF ENSO

Joel Michaelsen
Dept. of Geography
University of California
Santa Barbara, CA 93106

Considering the widespread oceanographic and atmospheric impacts of the El Niño-Southern Oscillation (ENSO) phenomenon, there are many possibilities for developing high resolution proxy climate indicators which could provide information about ENSO fluctuations over the last several centuries. A preliminary analysis of a number of such indicators over a short period of time was presented in Baumgartner et al. (1989), where it was argued that considerable improvements in accuracy and fidelity could be gained by combining proxy records from different sources and regions. In this report, three such indicators are compared: tree-ring chronologies from Southwestern United States and northwestern Mexico (Michaelsen, 1989); ice cores from Quelccaya ice cap in Peru (Thompson et al., 1984); and documentary records (Quinn et al., 1987).

The tree-ring index is based on the first principal component of seven chronologies from northwest Mexico, New Mexico, and southern Colorado (Michaelsen, 1989). The ice core data are from two cores extracted from the Quelccaya ice cap and include several variables: accumulation, $\delta^{18}O$, conductivity, and counts of particles of different sizes (Thompson et al., 1984). The documentary records are compiled from many sources and focus on events in coastal Peru and the eastern tropical Pacific (Quinn et al., 1987). The tree-ring and ice core data were all bandpass filtered to remove variability on scales longer than about 15 years and shorter than about 2.5 years (see Michaelsen, 1989).

There are two important sources of error in each of the proxy records which could reduce the correspondence between them. First, any proxy climate indicator will be an imperfect recorder of the climatic events it reflects. Second, these three specific indicators are responding to climatic events which are, themselves, only imperfectly correlated with the basic ENSO phenomena. The tree-rings reflect moisture in the Southwest which is only moderately correlated with standard ENSO records such as the Tahiti-Darwin southern oscillation index. The ice core records are from southern Peru, outside of the core region of ENSO influence, where the main moisture source is the Amazon Basin. Even the documentary records, which are concentrated in the core El Niño areas in Peru and the tropical Pacific, can be affected by local events that are not related to any of the large-scale ocean/atmosphere variations commonly associated with ENSO.

The three proxy records were first compared over the modern period for which instrument records are available. The three numerical indices of ENSO derived by Wright (1989) were used for this analysis. They are: an index of rainfall at island stations in the tropical Pacific (R-cap), 1894-1983; sea surface temperature averages for the central and eastern Equatorial Pacific (S-cap), 1881-1986; and a Southern Oscillation atmospheric pressure index based on the Darwin and Tahiti differences (DT-cap), 1851-1984. All three records were aggregated to annual averages to match the resolution of the proxy records.

Correlations between the proxy data and the instrument records (Table 1) show that the tree-ring index is significantly correlated with all the instrument records. It explains about 30-35% of the variance in the ENSO records. The $\delta^{18}O$ data is also significantly correlated with the ENSO records at the .01 level, while the total particle correlations are significant at the .05 level. Due to the intercorrelation between the two ice core records, a multiple regression using both does not perform significantly better than one using $\delta^{18}O$ alone. The latter explains about 20-25% of the variance in the ENSO records. Combining the tree-ring and $\delta^{18}O$ data produces a regression equation which explains up to 40% of the variance in the ENSO records. (Significance levels are based on a full 71 degrees of freedom. A more conservative approach would be to assume that the filtering retains about 1/2-2/3 of the original degrees of freedom. Calculations based on 35 degrees of freedom indicate that the tree-ring and $\delta^{18}O$ correlations are still significant at the .01 level while the total particle correlations are no longer significant.)

Table 1. Correlations of the tree-ring and ice core data with the instrument records for the period 1894-1964. One asterisk indicates significance at the .05 level; two asterisks indicate significance at the .01 level. All of the instrument records are defined to be positive for ENSO events.

	R-cap	S-cap	DT-cap
Tree-rings	.597**	.529**	.529**
Ice cores			
Accumulation	-.186	-.135	-.141
All particles	.258*	.261*	.212*
Large particles	.168	.189	.138
Small particles	.192	.211	.144
$\delta^{18}O$	.479**	.462**	.441**
Conductivity	-.007	.003	-.085

Comparisons with the categorical documentary records were accomplished by converting the continuous instrument and proxy data to categorical records. There are 12 strong or very strong events noted in the Quinn et al. records during the 1894-1964 periods, so the 12 highest years in each series were tagged as potential ENSO events. A test for independence between two categorical series can then carried out by counting the number of times an event occurs in both during the same year. Under the independence hypothesis the joint probability of finding matching events in both would be the product of the probabilities of finding events in each individual series, i.e., $(12/71)^2$. The expected number of matches is two, four or more matches are required to reject the independence hypothesis at the .05 level, and six or more to reject at the .01 level.

The number of matches between the Quinn et al. index and R-cap, S-cap, DT-cap, tree-ring, and $\delta^{18}O$ indices are six, five, five, four, and six, respectively. Thus it is possible to reject the independence hypothesis in all cases. Not surprisingly, the three instrument records are highly related to each other, with nine matches in all cases. The tree-ring and $\delta^{18}O$ are also more highly related to the instrument records. The tree-ring index matches each of the instrument records six times, and the $\delta^{18}O$ has six matches with one and seven with the other two. Finally, the tree-ring and $\delta^{18}O$ indices are highly related by this criterion with eight matches.

The longest of the instrument records, DT-cap, begins in 1852, so it is possible to get some indication of the fidelity of the proxy records over time by examining their behavior during the 1852-1893 period. The correlation between DT-cap and the tree-ring index drops only slightly to .516. The correlation between DT-cap and the $\delta^{18}O$ data, however, drops sharply to .121. An examination of the cross-correlation function suggests that the $\delta^{18}O$ series becomes offset from DT-cap by one year during this period. When a missing year is inserted in the $\delta^{18}O$ series between 1880 and 1881, the correlation with DT-cap increases to .490. A comparison of the documentary index with DT-cap and the other two proxy indices is somewhat tenuous due to the small sample size, and the results show that the assumption of independence between the documentary index and the other three indices cannot be rejected in any of the cases.

The tree-ring and $\delta^{18}O$ records were compared for the full period of overlap, 1570-1964, by calculating cross-correlations for overlapping segments. Three more instances where the two series became offset by one year were identified. It is not possible to be certain which series is shifted, but it seems likely that the $\delta^{18}O$ index is responsible, considering the fact that a missing year was located in the comparison with DT-cap and that the tree-ring index is composed of seven different chronologies. Consequently, the $\delta^{18}O$ record was adjusted by adding two missing years (1840 and 1731) and deleting one extra year (1692). After adjustment the correlation for the period 1570-1964 is .351. The cross-correlation analysis also indicates, however, that the relationship between the two records disappears completely prior to 1630. The correlation for the period 1630-1964 increases to .426. Finally, the two continuous series were compared with the documentary index for both the 1570-1964 and 1630-1964 periods. In all cases the number of matches was somewhat higher than would be expected by chance but not high enough to reject the assumption of independence.

In summary, comparisons of the three proxy records with the instrument records of ENSO indicate that the proxy records are related to the instrument records at a modest, but significant level. The tree-ring and $\delta^{18}O$ indices maintain a reasonably consistent relationship, after adjustment, back to about 1630, while neither shows a significant relationship with the documentary index for the full period. This lack of relationship could result from a number of different problems. First, it is possible that the way in which the continuous records were categorized might have an impact. More tests need to be done to assess the sensitivity of the results to the method of defining an event in the continuous series. Second, in some instances a two year ENSO event is identified in the documentary record while the other two series show peaks in only one of the years. This was treated as one match and one miss and might be reasonably treated as a full match. Third, during the modern period both the continuous series showed stronger relationships with the large-scale ENSO records than with the documentary index. Since they are both recording events that are remote from the core El Niño region, it may be too much to expect them to match well with the local El Niño variations. In regard to this issue, it would be very interesting to expand the analysis to include proxy records which are more directly related to oceanographic variations in the eastern tropical Pacific, such as the tropical Pacific coral records (Shen et al., 1987) or the Gulf of California varve records (Baumgartner et al., 1985).

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ENSO SIGNALS IN FOREST FIRE RECORDS

FROM THE NORTH AMERICAN SOUTHWEST

Thomas W. Swetnam, Laboratory of Tree-Ring Research, Univ. of Arizona, Tucson, AZ 85721; *Julio L. Betancourt*, U. S. Geological Survey, 300 W. Congress St., FB-44, Tucson, AZ 85701.

Wildfire occurrence in the southwestern U.S. is correlated with tree-ring growth, cool season precipitation, and December through February Southern Oscillation (SO) indices. Others have shown that an El Nino-Southern Oscillation (ENSO) signal exists in southwestern winter-spring precipitation records (Douglas and Engelhart 1984, Andrade and Sellers 1988) and tree-ring width chronologies (Lough and Fritts 1985, Michaelson 1989). Interannual variations in fire activity probably derives from the influence of winter-spring precipitation on the accumulation and moisture content of the fuels. By coincidence, tree growth response in southwestern conifers is primarily a function of cool season moisture; fire scars in tree rings also record local surface burns, allowing simultaneous solution of the fire-climate linkage.

A two hundred year record of regional-scale fire and drought patterns was reconstructed from fire scar and tree ring-width chronologies (1700-1905). Records of annual area burned in National Forests, monthly precipitation, and SO indices were compiled for the current century (1905-1985) (Fig 1). Comparisons of these data (Figs 2 and 3) reveal that ENSO phenomena may drive long-term patterns of vegetation dynamics in this region through the synergistic effects of climate, fuels, and fire. Inherent lags between SO, cool season precipitation and the fire season in late spring-early summer imply opportunities for predicting fire potential as much as a year in advance. The temporal and spatial relations between ENSO and fire as revealed in the tree-ring record, changes in these relations (Fig. 3), and paleoclimatic and ecologic implications will be discussed.

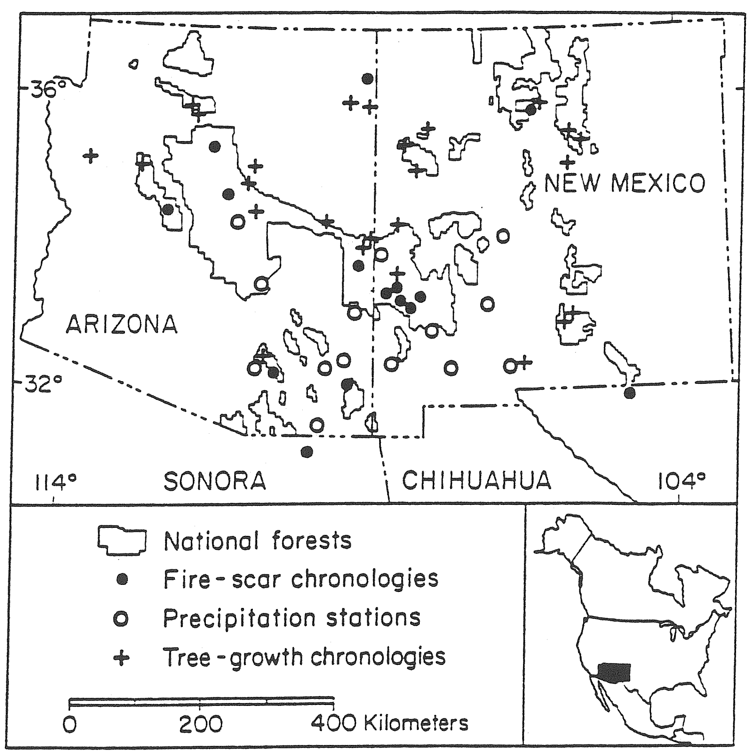

Figure 1. Locations of fire, tree-ring, and precipitation data sets.

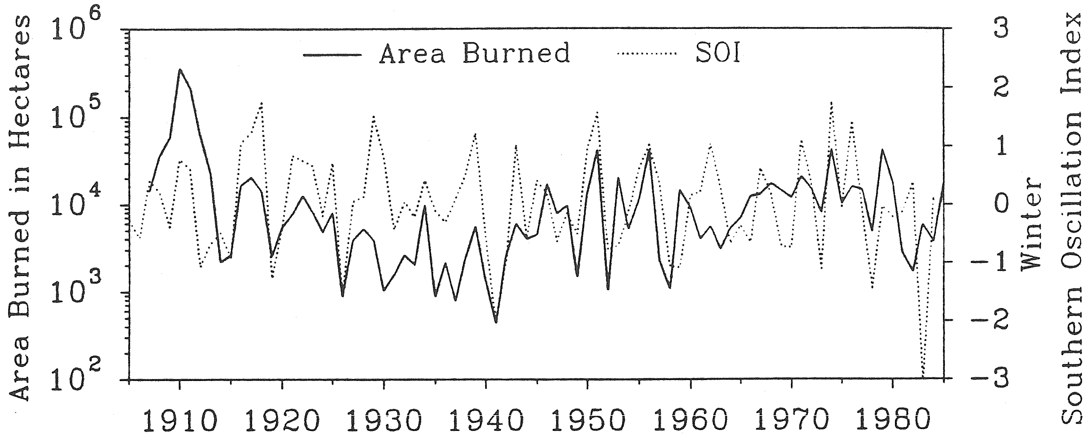

Figure 2. Time series of annual area burned in all National Forests in Arizona and New Mexico and mean December-January-February Southern Oscillation Index, 1905-1985. Pearson correlation is 0.354, p = 0.001. Unusually large fires before 1915 and increased numbers of human-caused fires after 1960 may partially confound the relationship. The correlation for 1915 to 1960 is 0.577, p < 0.001.

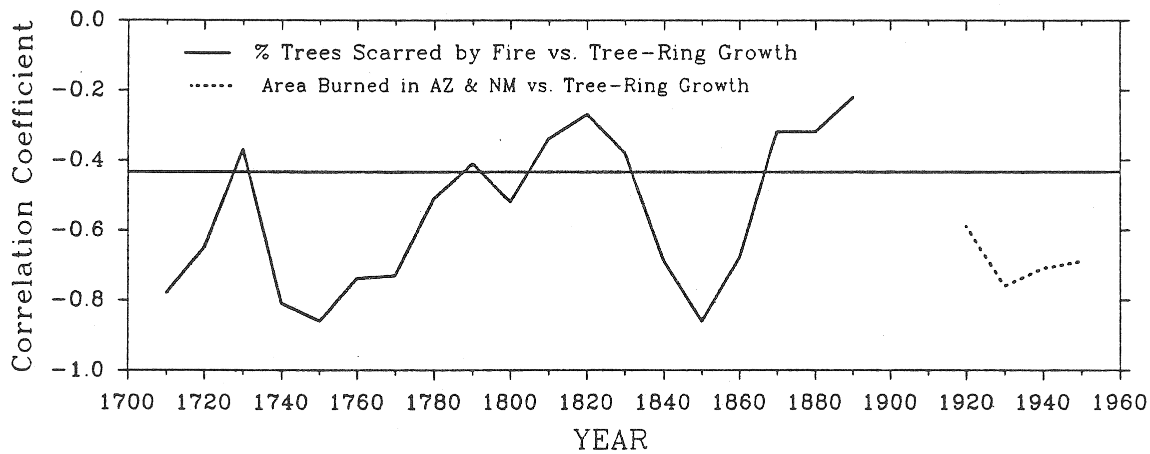

Figure 3. Pearson correlations for first differences of tree-ring growth from 28 sites, mean percentage of trees scarred per year by forest fires in 15 sites (solid line, 1700-1900), and area burned per year in National Forests (dotted line, 1910-1960). The correlations are for 21-year periods, plotted on the central year, and overlapping by 10 years. Significant inverse correlations at the p = 0.05 level fall below the horizontal line. High tree growth (wetter conditions) generally correspond to reduced fire activity, and vice versa.

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SOUTHERN OSCILLATION EXTREMES RECONSTRUCTED FROM TREE-RINGS OF THE SIERRA MADRE AND SOUTHERN GREAT PLAINS

David W. Stahle and Malcolm K. Cleaveland
Department of Geography
University of Arkansas
Fayetteville, AR 72701

A teleconnection between the El Nino/Southern Oscillation (ENSO) and cool season precipitation and temperature has been detected in meteorological data from northern Mexico and the southern Great Plains. Texas and Mexico tend to be cool and moist during the boreal winter of El Nino events, and warm/dry during La Nina events. This signal typically extends from autumn (year 0) into spring (year +1), but is usually not prominent during the height of the regional tree growth season in late spring and early summer. Nevertheless, the ENSO phenomenon definitely has an influence on tree growth in Texas and Mexico early in the spring growing season, and probably also by means of a long term effect on soil moisture depletion or recharge during the winter and spring. Statistically significant inverse correlations have been observed between a cool season average of the Southern Oscillation Index (SOI; P.D. Jones, personal communication) and most available post oak chronologies from the Southern Plains, and most conifer chronologies from high elevation forest of the Sierra Madre in northern Mexico (the Mexican data were provided by the University of Arizona Laboratory of Tree-Ring Research). Stepwise multiple regression analysis was used to select five widely separated SOI-sensitive chronologies from Durango, Chihuahua, Coahuila, and southern Oklahoma. These five prewhitened chronologies were entered as predictors into multiple regression analysis with a prewhitened winter SOI average as the predictand during the period 1900 to 1971. The winter SOI average was based on December, January, and February of year 0 and year +1, and was autoregressively modeled as an AR(2) with coefficients of -.03 and -.26. The multiple regression model based on the Mexican and Southern Plains chronologies was the best of several evaluated, and was associated with 45% of the prewhitened winter SOI variance, after downward adjustment for loss of degrees of freedom. The regression residuals are randomly distributed. A transfer function derived from the regression model was used to estimate winter SOI from A.D. 1699 to 1971, and the AR(2) persistence structure observed in the actual winter SOI data from 1866 to 1988 was added to the tree-ring estimates to complete the reconstruction. The tree-ring reconstruction was well verified by comparisons with independent SOI indices derived from meteorological data available from 1866 to 1899 ($r = 0.70$; reduction of error = +0.20).

classification and regression-based estimates with the actual winter SOI data available after 1865 indicate that both the classification and regression procedures are contributing unique information, and together should be providing a more accurate reconstruction of past ENSO activity. Considered together, the classification and regression estimates contradict few, and substantiate several negative ENSO events (El Ninos) identified with historical sources by Quinn et al. (in press) and Hamilton and Garcia (1986). The tree-ring estimates also suggest multi-decadal changes in the frequency and intensity of SOI extremes. These tree-ring chronologies could be usefully integrated with other annually resolved, ENSO-sensitive proxy data worldwide for a more accurate and detailed reconstruction of the ENSO phenomenon for the past 400 years.

THE SEARCH FOR AN ENSO-SIGNAL IN GREAT SALT LAKE FLUCTUATIONS

Paul A. Kay, University of Nebraska-Lincoln

Connie Woodhouse, Mountain Research Station, Nederland, CO

Most studies of midlatitude teleconnections to ENSO events have considered large scale (continental to hemispheric) patterns. Can an ENSO signal be detected confidently within a small region?

The drainage basin of Great Salt Lake is traversed by a winter season air mass boundary defined by Mitchell. The annual volumetric increase of the lake is a direct function of winter precipitation, so the lake should respond to variations in the position of the boundary, which as part of the larger-scale circulation should be a function of PNA patterns and in turn of ENSO events. Four tree-ring chronologies from the basin indicate that the basin has behaved as a distinct subregion within the larger intermountain west region, supporting the expected relationship of the lake to large-scale climate.

Seasonal volumetric increases are expected to be smaller than average in the years following the onset of ENSO events, which strenthen the PNA pattern and the ridge over the western United States. Seasonal volumetric decreases of the lake are expected to be an inverse function of summer cloudiness and precipitation. The expected relationship to ENSO is also inverse, with smaller than average decreases due to increased precipitation in summers with an onset of ENSO events. Examination of the historical hydrological record of Great Salt Lake with superposed epoch analyses, analyses of variance, and regression analyses, indicate only weak ENSO signals, often in directions other than expected. Transfer functions using the tree-ring chronologies only reproduce about one-third of the variance in either volumetric increase or decrease series. Paleoclimatic reconstruction of ENSO events, such as the southern oscillation index, are weak. These results are attributed to the distance of Great Salt Lake from the regions of maximum correlation with ENSO-teleconnections.

ENSO SIGNALS IN U.S. SOUTHWEST TREE RINGS

by David M. Meko

Laboratory of Tree-Ring Research
University of Arizona
Tucson, AZ 85721

ABSTRACT

Bivariate time-series transfer-function modeling was applied to study the lagged response of Douglas fir and pinyon pine tree-ring chronologies from the Galinas Mountains, New Mexico to ENSO-related precipitation variations, 1908-81. A slightly stronger precipitation and ENSO signal was found in the Douglas fir chronology. The precipitation signal does not appear to be distorted by autocorrelation in the tree-ring data for either chronology. Before 1950, ENSO events were generally associated with both high tree-growth and precipitation (September-May) anomalies in the current or succeeding year. From 1950-70, a time of decreased variance and lower mean in both tree rings and precipitation, the associations with ENSO events weakened considerably. It is suggested that low-frequency climatic variations may at times obscure the ENSO signal in the Southwest. Cross-spectral analysis of regional tree-ring series, 1700-1964, variability, and high squared coherency from Southern California to Colorado at the ENSO frequency band.

the overall analysis (see Fig. 3B), but the true significance of this apparent relationship is presently unclear.

As an additional test, Quinn's list of El Niño years was also used as key years in superposed epoch analysis. These years are similar, but not identical, to those obtained from Wright's index over the same 1850-1983 period. The results of using these key years were about the same as before, but the Texas results came out somewhat weaker. Quinn' list of El Niño years extending back beyond 1700 were than used in a more comprehensive test for ENSO signals in the drought factor scores. Again, the results were similar to before. Thus, at best, there appears to be only a weak ENSO influence on climate in the eastern United States as related to the development of summertime drought and wetness. While it is true that extremely strong El Niño's can have a strong influence on North American climate, on average the effect appears to be weak in the eastern U.S. Texas is the most strongly affected region after which any ENSO influence appears to diminish rapidly in space both north and east.

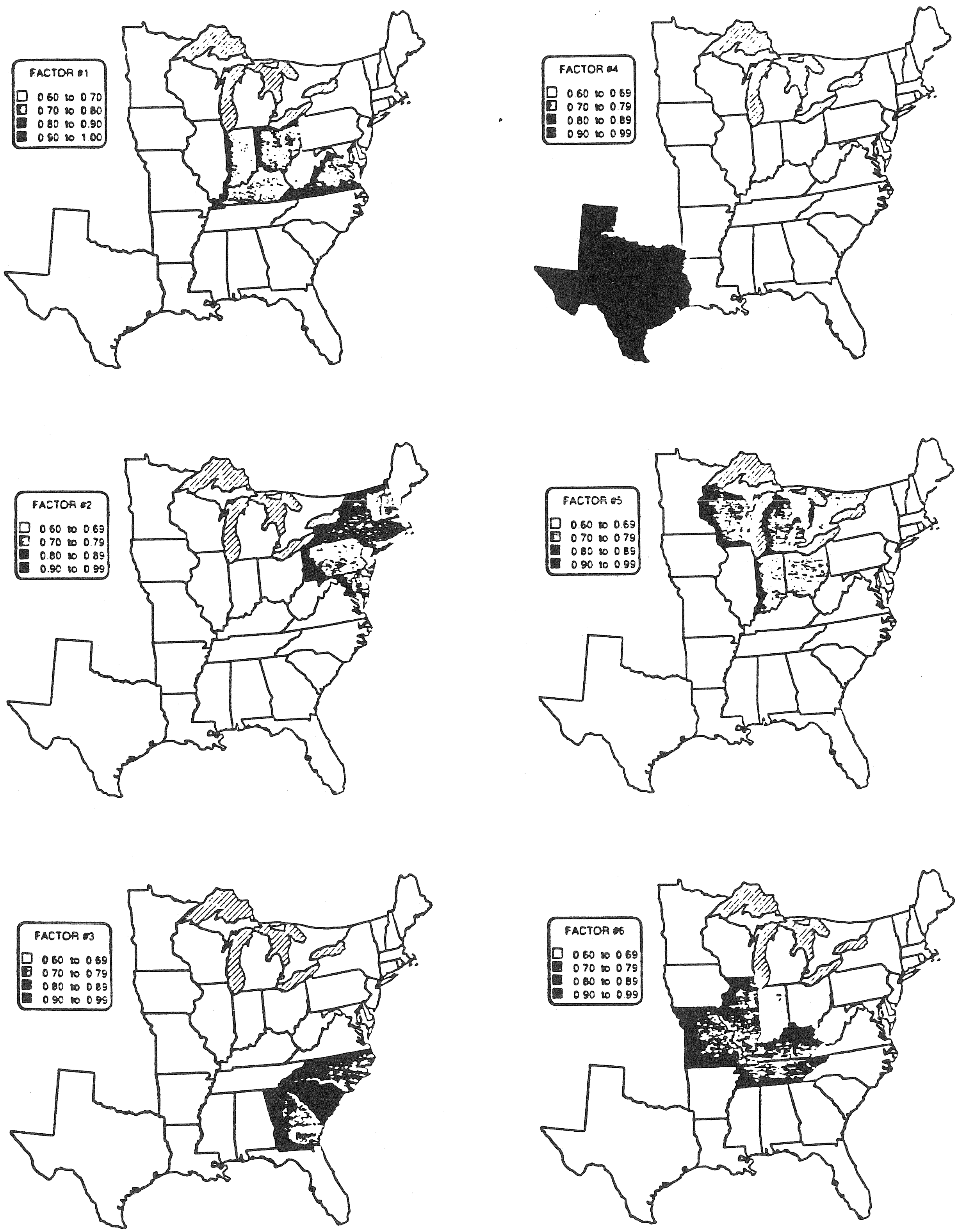

Fig. 1. Maps showing the locations of the drought factors used in this analysis. The shaded regions represent factor loadings exceeding 0.70. The factors are based on Harris-Kaiser oblique rotation of principal components.

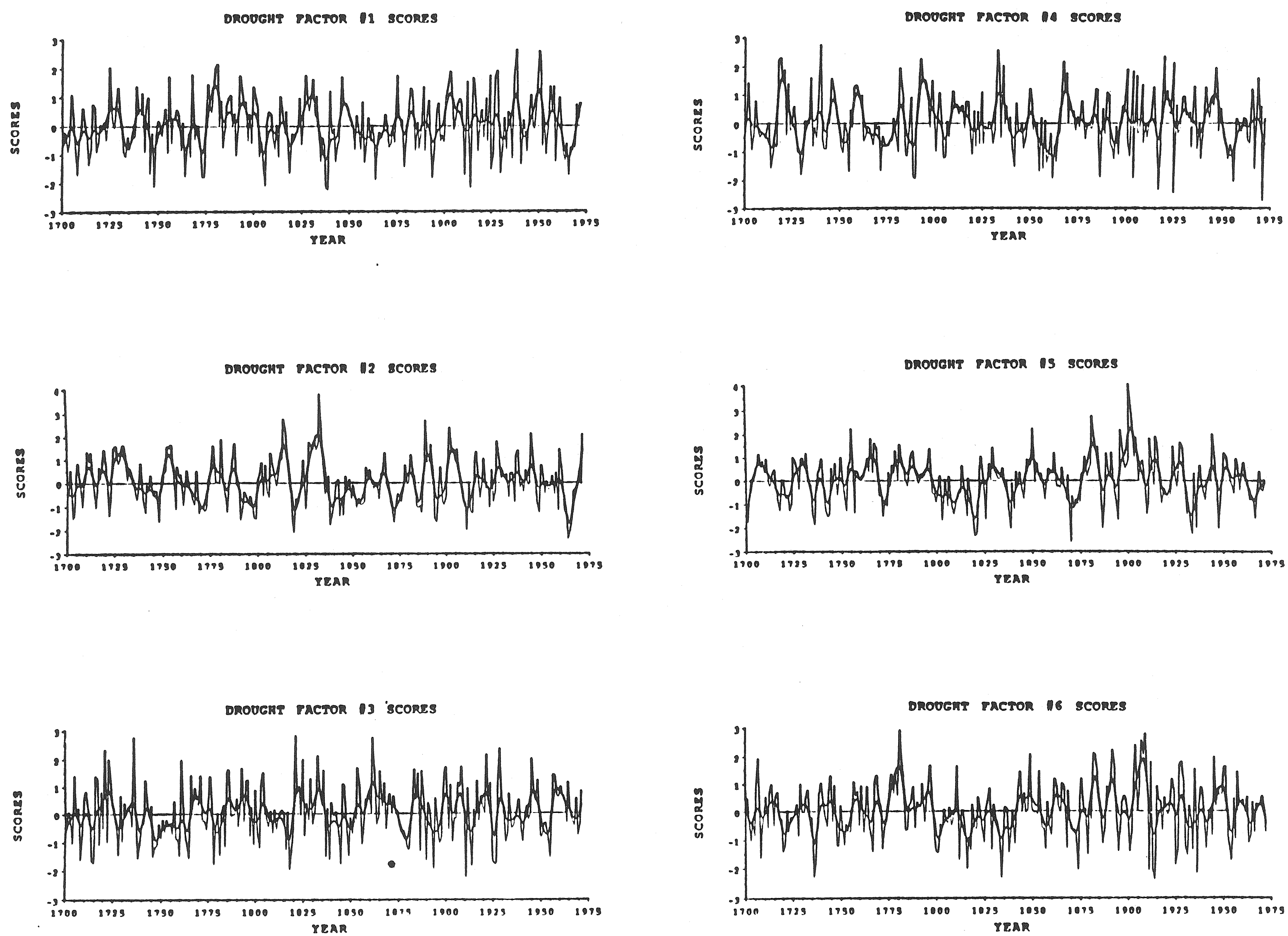

Fig. 2. The drought factor scores for the eastern United States. See Fig. 1 for the locations of these factors. Each series of scores was obtained from tree-ring reconstructions of summer drought for given states or regions.

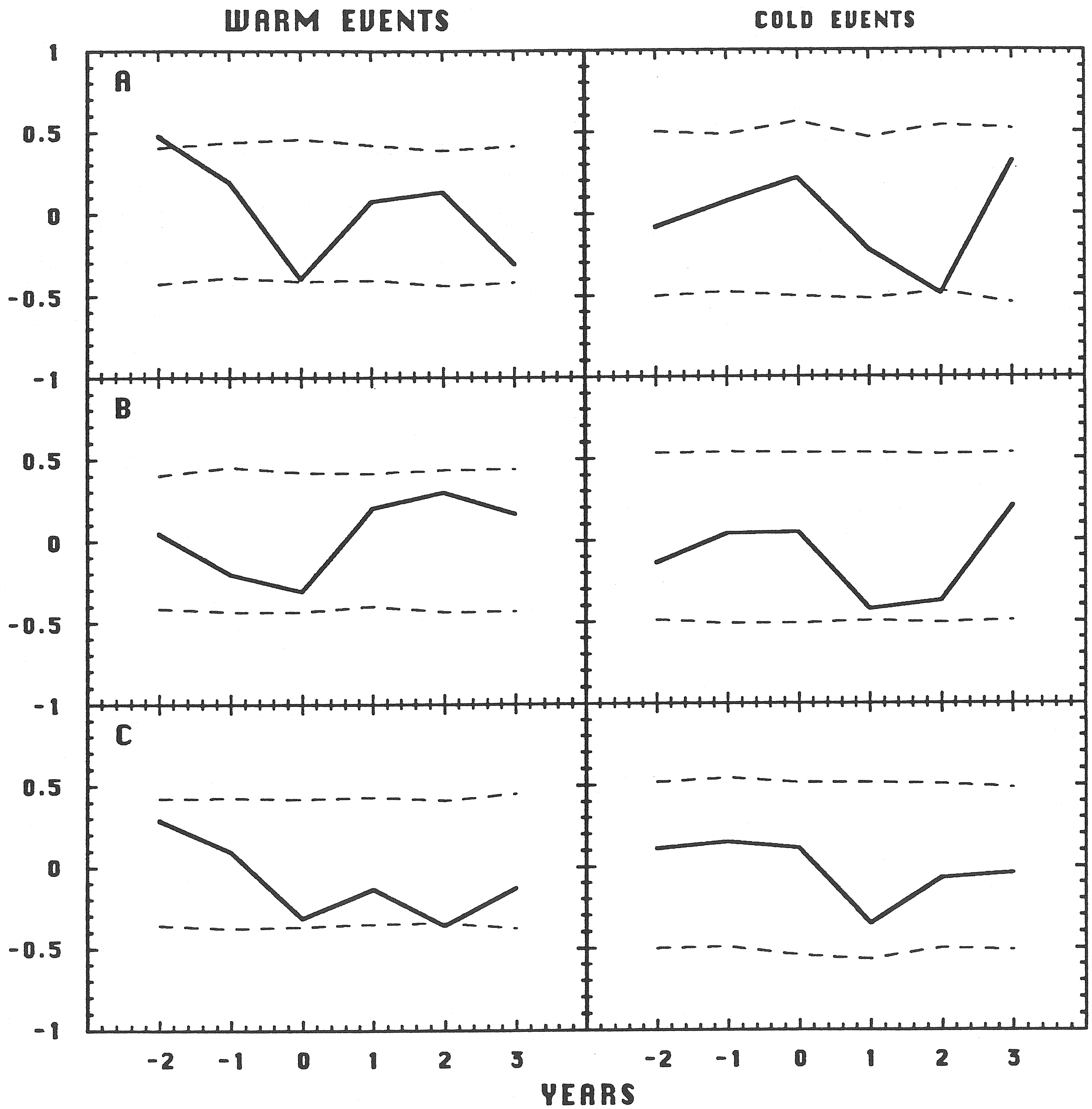

Fig. 3A. Superposed epoch results for the drought factor scores. A = Factor #1, the mid-eastern factor; B = Factor #2, the northeastern factor; and C = Factor #3, the southeastern factor. See Fig. 1 for maps of these factors and Fig. 2 for plots of the factor scores. The dashed lines are 2-tailed 95% confidence limits based on key year randomization. The heavy solid lines are the mean drought scores in normalized form for the years associated with warm (El Nino) and cold (La Nina) events. The events were selected from Wright's ENSO index.

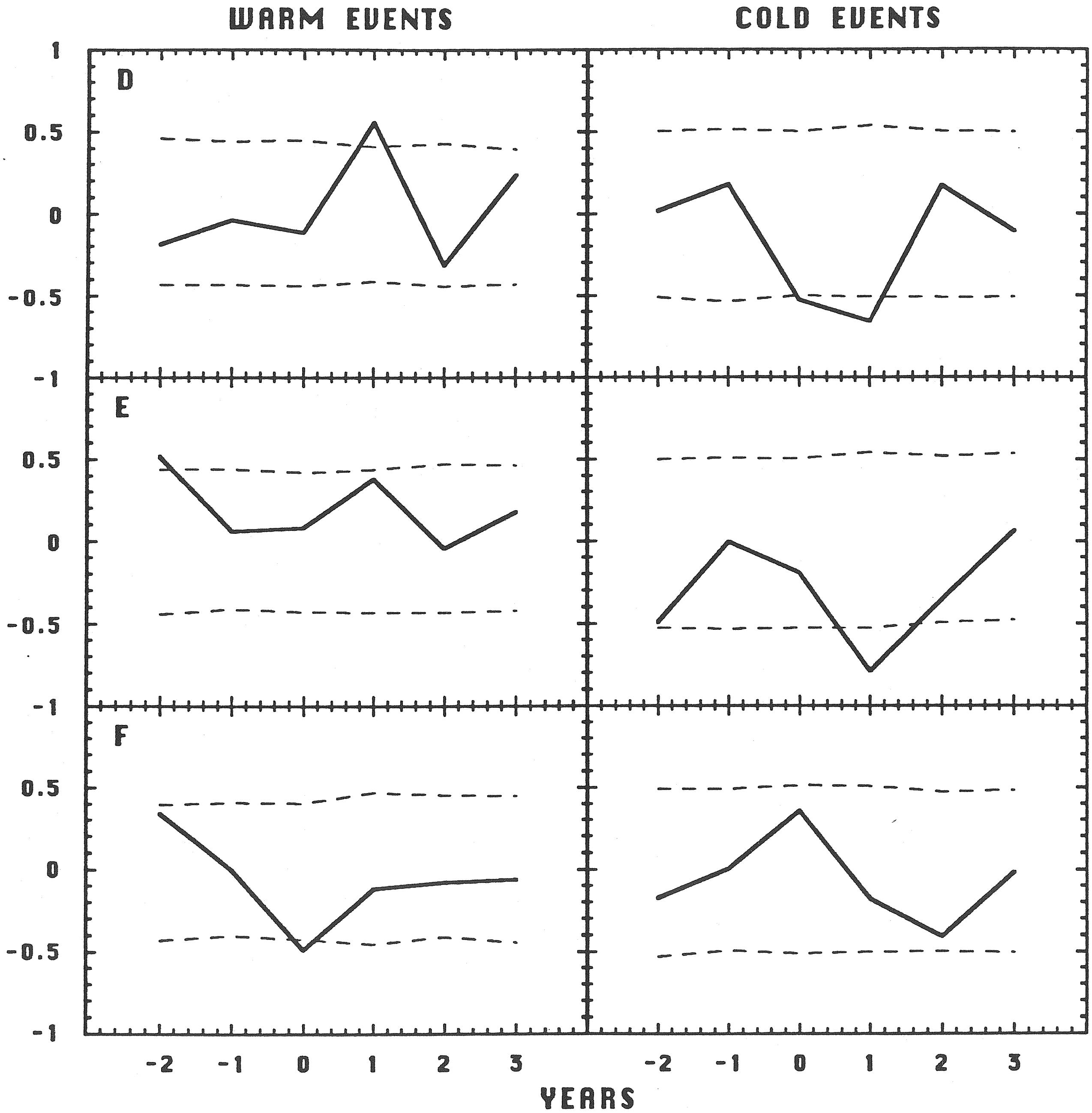

Fig. 3B. Superposed epoch analysis for the drought factor scores (continued). D = Factor #4, the Texas factor; E = Factor #5, the Great Lakes factor; and F = Factor #6, the mid-western factor. See the caption on Fig. 3A for more details regarding the meaning of these plots.

TROPICAL CYCLONE FREQUENCY, TERRESTRIAL FLOOD FREQUENCY, AND ENSO

Robert H. Webb and **Julio L. Betancourt**, U.S. Geological Survey, 300 W. Congress Street FB-44, Tucson, Arizona 85701 (602)-670-6821

The largest floods in the southwestern and eastern United States are caused by incursions of tropical cyclones, including hurricanes and tropical storms. In regions bordering the Gulf and Atlantic coasts, tropical cyclones, occasionally at hurricane strength, make landfall and dissipate over the continent. Tropical cyclones that develop in the eastern North Pacific Ocean usually dissipate over water or make landfall in Mexico, and residual moisture is transported over the southwestern United States by large-scale atmospheric circulation. The generation of tropical cyclones in both the North Atlantic and eastern North Pacific Oceans is decreased by the occurrence of El Nino - Southern Oscillation (ENSO) conditions in the equatorial Pacific Ocean. In the Atlantic Ocean, the number of hurricane days and total number of tropical storms and hurricanes per year is significantly reduced during ENSO conditions. The reduction is pronounced during strong and very strong ENSO conditions; however, large numbers of tropical cyclones have occurred during weak or moderate ENSO conditions or during the second year of ENSO conditions. In the eastern North Pacific Ocean, hurricane days and the number of tropical cyclones per year are also reduced, but ENSO conditions enhance upper level troughs over the west coast that are necessary for recurvature and dissipation of tropical cyclones over land. The result is an increased number of tropical cyclones that cause flooding in southwestern United States during ENSO conditions.

Examination of flood records in Arizona and Utah indicates that the frequency of incursions of dissipating tropical cyclones varied in the 20th century. Moreover, clustering of large floods in the prehistoric record suggests periods in the late Holocene of increased frequency of incursions of tropical cyclones. Changes in the variability and possibly the frequency of ENSO conditions and long-term shifts in the general-circulation steering mechanisms may partially explain changes in the frequency of dissipating tropical cyclones and, consequently, the occurrence of large floods in parts of the United States.

May 2-4, 1990 Workshop on Paleoclimatic Aspects of El Niño:

ENSO INDICATORS IN REEF CORALS OF THE EQUATORIAL PACIFIC

GLEN T. SHEN *UNIVERSITY OF WASHINGTON*
SCHOOL OF OCEANOGRAPHY, WB-10
SEATTLE, WA 98195

Owing to great differences in expression of the El Niño - Southern Oscillation in the eastern and western tropical Pacific regions, a variety of indicators in reef corals are being examined for their sensitivity to environmental change. McConnaughey (1989), Carriquiry et al. (1988) Druffel et al. (in press), Cole and Fairbanks (submitted), and Dunbar et al. (in prep.) have explored the use of stable isotopes as paleotemperature recorders in the east and as possible rainfall indices in the western basin. Physical growth parameters (band width, density) have been underutilized and may yield useful information (Lough, 1988; Dunbar et al, in prep.). Flourescence banding in Great Barrier Reef corals has been correlated with terrestrial runoff (Isdale, 1984), however, spatial variability on short distance scales can hamper the use of these markers as indicators of regional rainfall (Scoffin et al., 1989). A fourth class of paleoindicator, skeletal trace elements, has been described by Shen et al. (1987 and submitted), Lea et al. (1989) and Shen and Sanford (in press) in the context of upwelling and fluvial discharge. This abstract summarizes recent developments in the application of cadmium, barium, and manganese as ENSO indicators.

Published high-precision measurements of cadmium (normalized to calcium) in a live coral species from the Galapagos Islands have been extended to the usable base of the core band-dated at 1936 (sample duplicates are not quite complete). Eight of nine ENSO events between 1936-1982 identified by Quinn et al. (1987) as being of "moderate" to "strong" intensity are reflected by anomalously low Cd levels (measured quarterly). Interestingly, the "missed" 1939 M+ event is also not apparent in the Puerto Chicama SST series (COADS data near Galapagos are sparse for this period). Only one year is marked by low-Cd (1959) at a time when there is no record of unusually high SST. The quarterly Cd/Ca anomalies in *P. clavus* from Punta Pitt, San Cristobal Island are reproduced in Fig. 1 alongside quarterly SST anomalies computed from the Puerto Chicama dataset for the same time period. Apart from having captured the overall incidence of individual El Niño events, we note a few other observations. Cold periods, or anti-El Niño conditions are also generally reproduced. In fact, it is during strong upwelling that we notice the largest Cd anomalies, indicative of the pumping up of high nutrient levels to the surface ocean. Both warm and cold intervals, however, are often sustained in the coral chronology for only three months at a time (our minimum time increment) -- seasonal changes in Cd appear more rapid than in comparable measurements of SST. Part of this may reflect measurement error, however, another uncertainty relates to our assumption that the growth rate of *P. clavus* is roughly linear at Punta Pitt. If this is not the case, then some of our quarterly increments probably sample periods shorter than three months while other sections represent longer growth intervals. The need for high frequency sampling is obvious.

The above calibration lends confidence to an otherwise confused situation regarding the reliability of Cd based on analysis of two other corals from Urvina

Oxygen isotope records of the Southern Oscillation from Tarawa Atoll corals

Abstract, NOAA ENSO Workshop

Julia Cole
Lamont-Doherty Geological Observatory
Palisades, New York

In the western equatorial Pacific, the El Niño/Southern Oscillation (ENSO) phenomenon is characterized by precipitation variability associated with the migration of the Indonesian low pressure cell to the region of the date line and the equator. ENSO-related sea surface temperature changes are weak or absent in this area. ENSO conditions bring intense rainfall to Tarawa Atoll (1°N, 173°E). Measurements from nearby islands suggest that this precipitation has an estimated isotopic composition of -8 to -10‰ $\delta^{18}O_{SMOW}$. This rainfall alters the $\delta^{18}O$ of the surface waters, due to the thin surface mixed layer in this region. Oxygen isotope records from two corals collected off the reef crest of Tarawa reflect rainfall variations associated with both weak and strong ENSO conditions. These records capture even the relative magnitudes of the swings in the Southern Oscillation Index. Coral skeletal $\delta^{18}O$ variations due to small SST changes contribute to the isotopic signal but are secondary in importance to changes in surface water $\delta^{18}O$.

These results demonstrate the potential to reconstruct variations in the Southern Oscillation from coral $\delta^{18}O$ records in the western equatorial Pacific, a region which has few paleoclimatic records, yet is extremely sensitive to shifts in the Southern Oscillation. A complete understanding of the history of ENSO activity will require long records from sites sensitive to all of the various climatic/oceanographic components of ENSO - e.g., SST change in the eastern Pacific and precipitation changes in the central and western Pacific. The Tarawa record can be usefully compared with coral histories from the Galápagos Islands and Indonesia to distinguish the various meteorologic and oceanographic anomalies that characterize ENSO events from local climatic fluctuations. This comparative approach can be used to identify the different climatic signals of ENSO events across the Pacific.

reconstruction models. These teleconnection patterns were most clearly evident in the reconstructed temperature data. Thus, North American climate reconstructions appear to contain information about past variations of the SO (Lough & Fritts, 1985, in press).

3.2 Teleconnection patterns in the tree-ring chronologies

Averaging and differencing the 65 prewhitened tree-ring data for years of extreme low and high SO index revealed distinctive patterns of tree growth anomalies in the year following warm and cold events. Warm event years were associated with increased growth especially in Colorado, Utah, Arizona, New Mexico and Mexico and slightly reduced growth in Montana and southwest Canada. The pattern of growth anomalies was nearly the reverse following cold event years. The composite patterns of growth anomalies for the warm, cold and warm-cold event years (obtained from 20th century data) were then correlated with the yearly patterns of tree-growth anomalies back to 1602. Using a pattern correlation cut-off of $r=0.5$ (no allowance made for spatial correlation in the data field), this procedure identified years with similar patterns of growth anomalies as those associated with SO extremes in the 20th century. In the period since 1877 most, but not all, occurrences of the composite patterns followed respective warm or cold events. There were, however, years in which these patterns did occur that were not associated with warm or cold events and also warm and cold events not clearly associated with these patterns. For example, for the major ENSO event of 1877-1878 the pattern correlation with the warm tree-ring composite was -0.33!

3.3 Reconstruction of an SO index from North American trees

The 65 prewhitened tree-ring chronologies were used to estimate seasonal values of the Tahiti-Darwin SO index. Such a reconstruction was limited by a) the strength of the SO signal at mid-latitudes, b) the non-uniqueness of the SO signal and c) tree-ring chronologies only explain a portion of climate variance. A statistically significant reconstruction of the SO was obtained. The reconstruction explained between 18-59% of the variance with between 4-33% of the variance verified (according to the season considered). The most reliable reconstruction appeared to be that for the DJF value of the SO index. Examination of the contributions of the original tree-ring chronologies to the final reconstruction showed that the major contribution was from trees at sites in the southern United States, extending into Mexico (inverse), a weaker centre in the Pacific northwest (inverse) and a positive contribution from trees in the centre of the network. Spectral analysis of the reconstruction (Figure 1) showed significant peaks at 3, 5 and 10 years. The higher frequency spectral peaks were more evident in the most recent 120-year period (1841-1960) and the lower frequency spectral peaks in the 120-year periods 1601-1720 and 1721-1820. For successive 50-year periods the estimated number of low and high index events ranged from 21 for 1651-1700 and 1901-1950 to only 10 for the period 1851-1900. Some agreement was found between the reconstructed SO values and the occurrence of El Nino events (Quinn et al., 1987).

3.4 Southern Hemisphere tree-ring chronologies and the SO

An attempt to reconstruct the SO index from the 33 S.H. tree-ring chronologies was not as successful as that from the western North American tree-rings (Lough & Fritts, 1985). Examination of the correlation between the prewhitened chronology series and the S.H. summer average values of the SO index over the common period 1867-1973 showed a few weak, but significant correlations between tree growth in Tasmania and New Zealand and the SO. These correlations were inverse i.e. increased growth with low index values. The magnitude of the correlations and their stability through time was, however, much less than that found for the North American network. The S.H. network of tree-ring chronologies did not appear to contain a very strong signal related to the SO. This result may attributed to a) the poor characteristics of the S.H. chronologies (i.e. poor replication and low inter-tree correlations), b) our limited understanding of the ecology of S.H. tree growth (Norton, 1988) and c) the trees being located at sites that are not consistently influenced by the SO.

4. Conclusions

- North American climate is significantly influenced by the SO and this influence is evident in both tree-ring chronology series and reconstructions of climate derived from such data.

- The patterns of anomalies in western North American trees associated with extremes of the SO are not unique to SO years.

- A significantly calibrated and verified reconstruction of an SO index can be derived from western North American tree-ring chronologies. The practical significance of this reconstruction is probably low though analysis of the reconstruction suggests some possible variations in the SO since 1600 A.D.

- Tree-ring chronologies from temperature latitudes of the S.H. do not show a strong signal in association with variations of the SO. Understanding of the climate response of such trees is required as well as identification of sites where the SO signal is more consistent.

- The above analyses, based on mid-latitude teleconnections with the SO demonstrate that tree rings can provide some information about past occurrences of the SO. This information needs to be combined and integrated with independent proxy climatic information to provide the most realistic picture of SO variations in the past.

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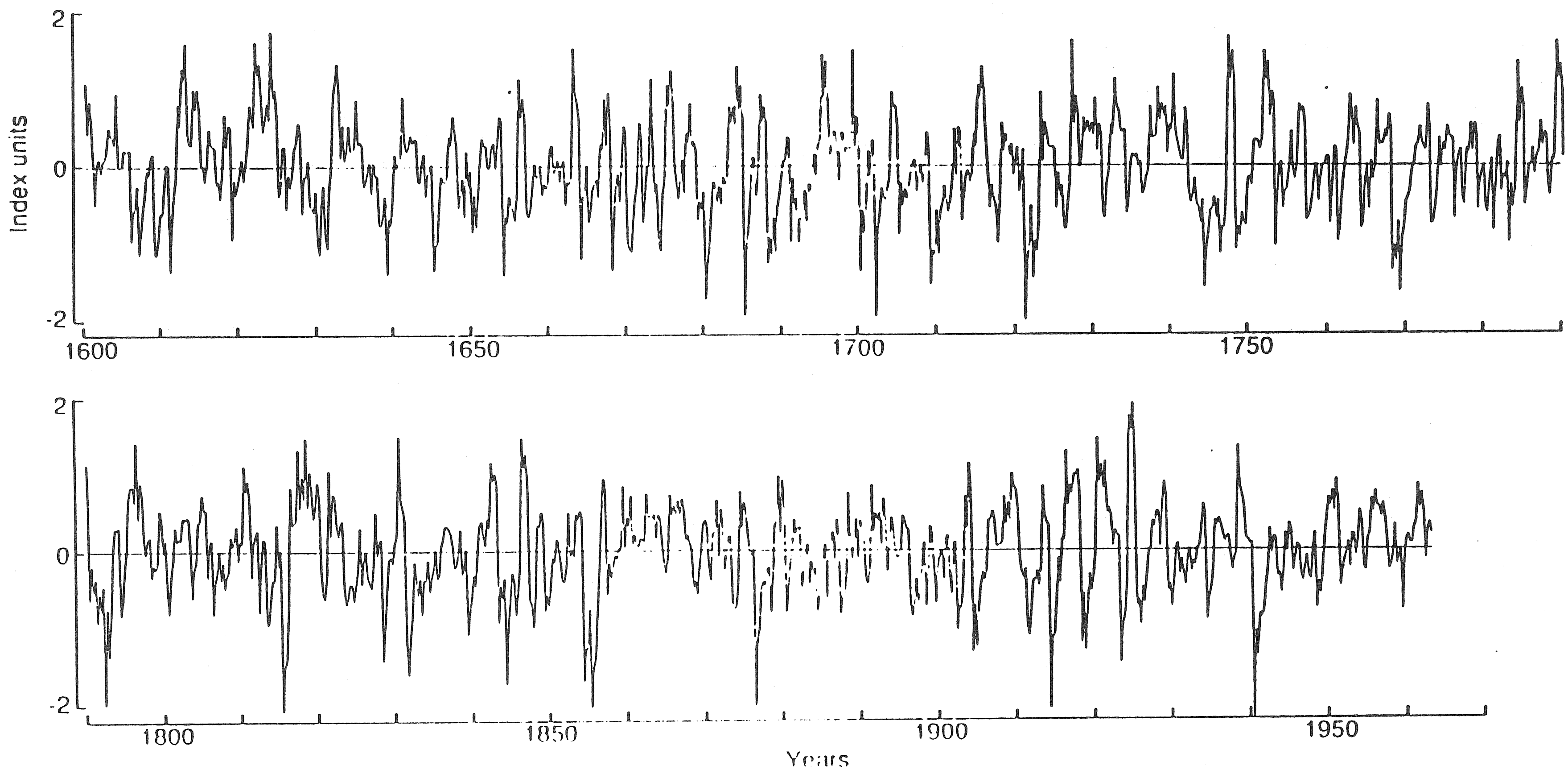

Figure 1: Reconstruction of seasonal SO index values from JJA 1600 A.D. to MAM 1963 A.D. from western North American tree rings.

ENSO Signal in Drought-Sensitive Tree-Ring Records from the Southwestern United States and Java, Indonesia

Abstract

Rosanne D'Arrigo
Tree-Ring Laboratory
Lamont-Doherty Geological Observatory
Palisades, New York 10964

Six millenium-long tree-ring records from moisture-sensitive sites in the southwestern United States are used to reconstruct November-May rainfall for northern New Mexico for the years 985-1970. Two of the most prolonged and severe droughts were found to occur during the past century: in the 1890's-1905 and the 1950's-early 1960's. These were exceeded in length and severity only once in the reconstructed record, in the late 1500's, and almost equaled in the early 1200's. The most abrupt shift from severe sustained drought to extreme high precipitation occurred from the 1890's to early 1900's and is unprecedented over the 1,000-year period of the reconstruction. Relatively dry conditions are reconstructed for the 1400-1600's period of the Little Ice Age.

The southwestern U.S. is a region of known teleconnection with ENSO events, coinciding with a tendency for wetter conditions to occur in this area during ENSO years. The above chronologies and reconstruction show correspondence with several indices of ENSO. For example 1720, 1816 and 1941 (interpreted as ENSO's in instrumental and/or historical data) are the 1st, 3rd and 4th wettest individual years in the above reconstruction. Variance spectral analysis reveals significant peaks corresponding to those of ENSO events as described in other records. There is potential for modeling the amplitude and frequency of ENSO over the past 1,000 years of record.

A 400-year (1514-1929) tree-ring series of teak or *Tectona grandis* was developed by Berlage in 1931 and derived from Java, Indonesia, a region directly influenced by ENSO. Reanalysis confirms a relationship with drought variations associated with ENSO events. There is considerable dendroclimatic potential for exploiting this species in future studies related to ENSO and tropical climate variability.

Long-term changes in the ENSO cycle as measured in marine sediments

Roger Y. Anderson, Department of Geology, University of New Mexico, Albuquerque, NM 87131

The effects of ENSO are preserved in late Pleistocene varved marine sediments accumulated along the upper continental slope off California and are recognized as zones of millimeter-scale laminations (varves) alternating with with zones of bioturbation. Bioturbated intervals are believed to correspond to weakened circulation associated with El Niño events. Conditions that exclude bioturbation and lead to the preservation of varves are believed to include a decrease in concentration of dissolved oxygen in the oxygen minimum zone that is linked to higher productivity and bacterial oxygen demand. Higher productivity is linked to higher nutrient concentration, increased offshore Ekman transport and upwelling, and a stronger California Current; such conditions are associated with the anti-El Niño (La Niña) regime and are tied to increased wind stress related to amplification of the high pressure cell in the eastern Pacific and/or the continental thermal low over western North America. Varve/bioturbation cycles similar to those in the late Pleistocene are found in the Miocene Monterey Formation, suggesting that an ENSO-like system is a persistent feature of Pacific circulation.

Zones of varved and bioturbated sediment alternate on a physical scale ranging from millimeters to decimeters and on a temporal scale ranging from a few years to several millennia, with decadal cycles near 20 years and 80-90 years identified in available late Pleistocene sequences. A period near 80-90 years has also been identified in cyclic changes in the frequency of historical El Niño events. The historical cycle appears to have an inverse association between the frequency of El Nino events and sunspot number.

Biologic and sedimentologic parameters associated with the summer season of upwelling off California are characteristic of the anti-El Niño circulation regime. Winter-season associations are generally characteristic of El Niño conditions. The associations between components established in summer and winter are repeated during decadal varve/bioturbation cycles, and repeated again in longer and stronger millennial varve/bioturbation cycles. Hence, long-term changes in ENSO appear to find expression through the annual cycle and the prime ENSO cycle and have a consistent association of components and responses to climatic forcing across a broad band of lower-than-ENSO frequencies.

THE SENSITIVITY OF NATURAL HIGH-RESOLUTION RECORDS TO ENSO VARIABILITY

TIM BAUMGARTNER

The purpose of this presentation is to examine the natural processes responsible for the underlying mechanisms of data acquisition and recording by high-resolution proxy systems with the objective to better understand and interpret the paleoclimatic data sets. This reduces to the question of what determines the sensitivity of a natural proxy system. Put in slightly different terms, it requires us to define with all possible certainty, what climatic signal we are reconstructing from a proxy set of ring-widths, isotope fractionation, microfossil counts, or whatever parameter we select to represent the response of the recording system to climatic change. Although this may seem trivial, it is quite possible to misinterpret valid raw data sets from mistaken inferrences which appear completely reasonable in the absence of information to calibrate the recording system to climatic forcing (cf. Baumgartner et al., in press).

The high-resolution systems resulting from seasonal growth (tree rings, coral bands) or depositional processes (varved sediments, glacial ice layers) are all reasonably well tuned to respond to the interannual scale of climatic variability dominated by the ENSO phenomenon. Of course, each of the systems records a unique response to different processes within the ocean and/or atmosphere. The fidelities of the systems therefore vary as a function of how well the particular local physical climatic process which drives the proxy system is itself coupled to the global-scale ENSO (Baumgartner et al., 1989).

In order to understand the factors which govern the sensitivities of these natural systems, we need to be able to do two things. First we should be able to clearly trace the chain of information flow from the global-scale variability which is at the heart of the ENSO phenomenon down to the local process which regulates the incorporation of information (now translated into the format of some local system parameter such as tree-ring width, microfossil species composition or isotope ratios) into the natural material record. I will use the Gulf of California as an example of a high-fidelity system in which we are now beginning to unravel the trail of processes which leave a record of global climatic variability in a local accumulation of mud.

The second component which I believe is necessary to defining and understanding the sensitivity of the natural systems is a clear idea of the basic dynamics of data acquisition and recording which is commom to all of the systems. This has led me to develop a general conceptual model of the processes by which environmental quantities (e.g. temperature. rainfall, oceanic nutrient concentration) are translated within a natural physical or biological system, to produce a multichannel record through several different procedures of signal modulation (cf. Bendat and Piersol, 1971). This presentation will therefore include an attempt to characterize the underlying processes which link all the natural high-resolution paleoclimatic recording systems.

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CLIMATIC SENSITIVITY OF BIOLOGICAL COMPONENTS IN THE LAMINATED SEDIMENTS OF THE SANTA BARBARA BASIN

A. Soutar

Abstract:

From the perspective of high resolution paleoclimatology, variability in climate on interannual to decadal time scales can be conveniently divided into local, regional, hemispheric and global areas of influence. While the mechanics and scales of day to day weather dictate overall connections between such divisions, intricate heat transfer processes in the atmosphere and ocean dominate and confound comprehension. A given set of climatic conditions at one scale may demand compliance, opposition or indifference at other scales. In this sense any one local climate may not clearly reflect global climate change; however, propitious placement in climatically sensitive regions or extreme developments in global climate are likely to be quickly noticed in local climate and records. Yet it is in fact the aggregation of local climatic records that to a large extent defines global climate; moreover, it is the absence and uncertainty associated with local records that clouds a verified assessment of global climate

In the above context the study of laminated marine sediments as a record of local ocean history may appear to have limited value in the current political climate that is focused on the global analysis of climate change in terms of geo-gas driven warming. However, given the paucity of long-term records of biologic activity in the ocean, the natural and hard record of marine varved sediments represent at least a few good locations on the surface of the earth where the interaction of climatic change and biology of the ocean can be intimately considered. Furthermore, an understanding of the sensitivity of coastal ocean biologic systems to interannual and decadal climate variability and the further understanding of the incorporation of system components into the year by year sediment record is the pathway to gain understanding of both local climate variability and coastal biologic systems over centennial and millennial time scales. Appreciation of the processes associated with sediment record formation at the local and regional scale can then only enhance understanding of ties that do exist to climatic change at the hemispheric and global scales

Clearly only a portion of biologic activity in the ocean results in traceable residues able to survive the sediment environment. In fact in the case of the Santa Barbara Basin the bulk of the record is actually terrestrial clays and fine silts. Nevertheless, a wonderful assortment of components can be found in each of the yearly sediment layers. Some idea of the richness of the record can be seen in Table 1 which is an attempt to document published and ongoing work. One interesting aspect of the sediment record is that the selection of components is a natural one; therefore, the rules that govern selection and emphasis may not necessarily appear to favor current research ideas or national needs. However, it must be stressed that yearly sediment records such as those encountered in the Santa Barbara Basin reflect real events and actvity in the overlying ocean. The task is then to reconcile the perception of climate we gain from instrumental records with the reflection

of ocean activity provided by the sediment records. Moreover, contrary to what one might presume, the problems associated with this venture do not entirely lie with the sediment record. While the natural system has for a long time and is still to this day collecting and preserving a modest but continuous phsysical and biological signal, mankind is only managing an inadequate and intermittent sampling over a marginally greater area. In physical climate terms the instrumental measure was either made or it was not. No further action can materially increase the extent or the precision of the record. In the case of the sediment record in some cases much can be done to increase the areal extent and a great deal can be done to increase the statistical precision of the record through sample replication.

The present report represents a step towards evaluation and interpretation of the Santa Barbara Basin laminated sediment record in terms of local sensitivity to ENSO as a hemispheric wide phenomenon. On one hand, available instrumental records are assembled to provide a view of local and regional California climate with an emphasis on ENSO related conditions. On the other hand, available biogenic component records are assembled with an emphasis on temperature. Comparison of the two record sets provides the basis for some observations on the applicability of the long established paleoclimatic paradigm that relates cold water species to cold water conditions and warm water species to warm water conditions. Furthermore, the record comparisons also provide for some comment on the more recently established California Current productivity paradigm that holds that organic production is markedly and generally reduced during periods of strong ENSO influence.

Table 1.

CONDITIONS, PROCESSES and EVENTS RECORDED in the SANTA BARBARA BASIN VARVED SEDIMENTS

Category	Condition/Process/Event	Recording Component	Reference
Temporal			
	time-0.5yr (10yr max)	U series Th-228/Th-232	Bruland & others, 1981
	time-2yr (150yr max)	atmospheric Pb-210	Bruland & others, 1981
	time-50yr (25,000yr max)	atmospheric C-14	Emery & Bray, 1964?
		alternating lamina sequence	
	time-1yr (138yr max)	in relation to regional rain	Soutar & Crill, 1977
	time-1yr (1000yr max)	and tree growth	Byrne & others, press
Terrestrial			
	plant growth	pollen	Heusser, 1978
	wildfire	charcoal	Byrne & others, press
	anthropogenic activity	Pb (gasoline)	Chow, 1973
		petroleum HMWHC	Crisp & others, 1979
		chlorinated hydrocarbons	Hom and others, 1974
	rainfall/runoff	varve thickness	Soutar & Crill, 1977
Marine	primary productivity	diatom spores	Lange & others, press
		organic C-13/C-12	Dunbar, 1981
			Schimmelmann, current
		bioactive metals	Dymond, current
	secondary productivity	planktonic gastropods,	
		planktonic foraminifera	Soutar, current
		radiolarians	Kling, 1977
	pelagic fish abundance	fish scales	Soutar & Isaacs, 1974
	upwelling	diatom spores	Lange & others, press
	California Current flow	radiolarians	Pisias, 1978
Climate	temperature	del O-18/O-16 (pl. forams)	Dunbar, 1981
		microfossils	Soutar, current
	ENSO	radiolarians	Weinheimer & others, 1986

Holocene history of the El Niño phenomenon as recorded in flood sediments of northern coastal Peru

L.E. Wells, Department of Geography, University of California, Berkeley CA 94720

The El Niño phenomenon perturbs the ocean-climate system of the Pacific basin episodically and is related to anomalous weather patterns worldwide. The normally hyperarid conditions of the Peruvian coast result in a direct correspondence between terrestrial flooding and the El Niño phenomenon. Precipitation data for the last 25 years indicate that exceptional rainfall north of 10°S latitude occured exclusively during El Niño incursions of warm water into the Peruvian littoral. The flood record is therefore believed to be a good proxy for very strong El Niño events. A set of 27 radiocarbon dates on overbank flood deposits from the Casma region (9°S) were used to establish a chronology for flood events during the last 3500 years. Due to the erratic pattern of flood plain deposition it is unlikely that the sedimentary deposits record every large El Niño event, however these data do suggest that flood events much larger than that which occurred during 1982-1983 occur here at least once every 1000 years.

Climatic variability in Australian paleoenvironmental records

A. Peter Kershaw
(Dept. of Geography and Environmental Science, Monash University)

It has been demonstrated from the analysis of rainfall fluctuations (Nicholls 1988) and river flow patterns (Whetton *et al.* 1990) that a major component of climatic variability in the Australian region is related to ENSO and anti-ENSO events. It has also been suggested that ENSO has been operating for a significant period of geological time from characteristics of the Australian flora and fauna that show marked adaptation to variable climatic conditions (Nicholls 1989). This paper examines data from palaeoenvironmental records that might shed light on the activity and significance of ENSO in the late Quaternary, prior to the period of historical documentation. It will also address the potential for identification of ENSO signals from the kinds of sites and techniques available for analysis.

To my knowledge, there has been no study undertaken in Australia to date specifically designed to identify ENSO signals in the pre-historic record. However interest in the phenomenon is increasing and changes in activity have been used recently to help explain certain features in specific site records. There are certain dangers to invoking ENSO as a cause of features in isolated records because of local, peculiar characteristics of individual sites and their changing sensitivity to palaeoclimatological conditions. For these reasons it is intended to first look at the broad regional paleoenvironmental picture to provide a firm basis for attempting to isolate ENSO influences from other causes of variablility. Emphasis is placed on periods of apparent instability in records, including preferred times of change, from pollen, sedimentological and charcoal data.

Some indication of the late Quaternary history of Australia is provided in Figure 1. The compilation of radiocarbon dates is from those areas for which a significant amount of palaeoecological research has been undertaken. Only those dates which age a sedimentological or palaeoecological change are included. The selection of sequences with continuous records provides some check on the validity of dates, although, as the majority of sequences from Australia are very condensed and have been subject to phases of erosion or non-deposition, gross approximations and inaccuracies in dating are likely to have occured. Individual dates are spread over three centuries to take some account of dating errors. 300 years provides an approximate average of one standard deviation on dates within the Holocene period. The records are terminated at 25,000Ka as, before this time, dates are few and concern is increasing that they may be unreliable.

It is clear from the regional compilations that there are preferred periods of change and relative stability although these are frequently not synchronous between regions. In general terms, the patterns of change and inferred climatic conditions can be explained by global temperature and sea level changes. A loose scatter of dates around 23-21Ka marks a gradual climatic deterioration to the cold and dry glacial maximum. This is succeeded by a very dry arid phase from about 15-12Ka which most likely resulted from an early temperature increase. About 11.5Ka precipitation levels also increased marking the beginning of organic sedimentation at many sites. Precipitation continued to increase, perhaps in a stepwise fashion, to a maximum between 7 and 5.5Ka where few dates occur. Maximum temperature levels may have been reached early in the Holocene although highest levels are frequently inferred for the climatic 'optimum' or even later. Recent BIOCLIM estimates are revealing the importance of seasonality and cloud cover in estimation of the temperature component. Precipitation and temperatures generally decrease after 5Ka reaching relatively low levels around 3.5Ka in most areas before a precipitation rise centred on 2.5Ka.

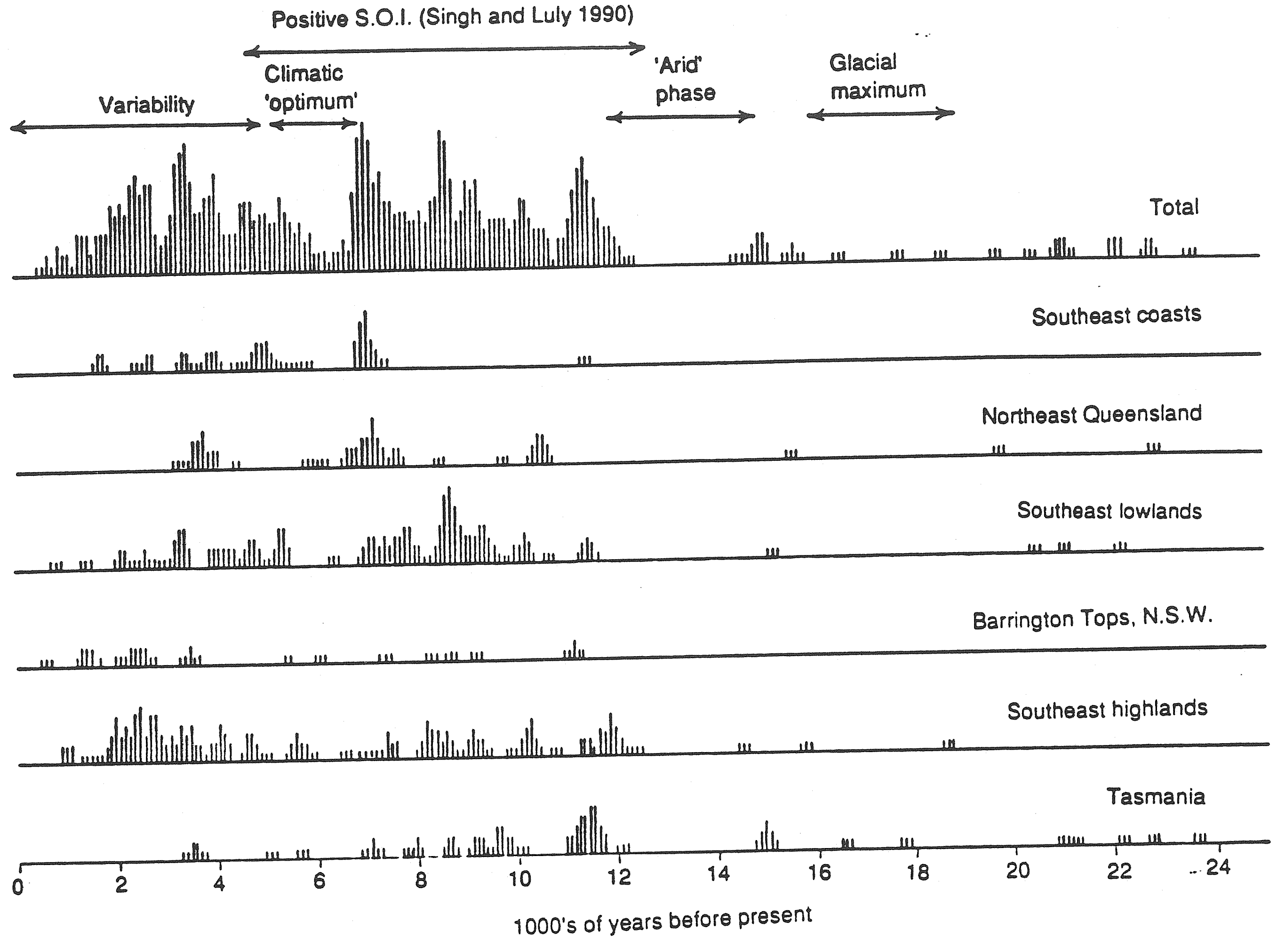

Figure 1. Radiocarbon dates from palaeoecological sequences

Evidence of variability and instability that might be related to ENSO are concentrated within the late Pleistocene arid phase and within the last 5Ka. Information from the earlier period is largely in the form of deposition of coarse sediments. Here, erosion could have been facilitated by very variable rainfall at a time when there was an incomplete vegetation cover. A number of lines of evidence contribute to the picture of late Holocene variability. These include:

1. interannual finely laminated sediments from miromictic lakes in northeast and southeast Australia,
2. higher levels of pollen from secondary rainforest plants from sites in northeastern Australia,
3. BIOCLIM estimates from rainforest taxa of increased seasonality in northeastern Australia,
4. inferred increased continentality in the Snowy Mountains, and variability in highland Tasmania from changes in dry land plant pollen.
5. higher burning levels in the Central Highlands of Victoria,
6. suggested less frequent incursions of monsoonal rains at Lake Frome, central Australia,
7. cyclical peat deposition and erosion in a spring-fed stream valley in central Queensland that could be caused by extreme events about every 500 years,
8. widespread slope instability on the southern tablelands of New South Wales.

However many of these features may have an anthropogenic rather than a climatic cause. The evidence for disturbance or variability in rainforests of northeastern Queensland corresponds with the archaeological evidence for the presence of people there and, although it is known that Aborigines had colonised most other parts of Australia for the last 30-40Ka, many archaeologists have argued for intensification of occupation with increased use of fire within the last 4-5Ka (Head 1989).

It has been proposed that strong ENSO signals are evident at times of major climatic change. In several Australian records it has been noted that charcoal peaks correspond to these times although this has been explained by fires being more effective and intense when the vegetation is under stress rather than by climatic variability. The apparent 2000 year periodicity of dust peaks in ocean cores off northern Australia within the late Pleistocene might also be explained by instability caused by more intense burning at times of major climatic and vegetation change rather than by periods of ENSO activity as proposed by De Deckker (in prep.) although this periodicity is not apparent from the compilation of dates from the terrestrial sequences.

Resolution of the relative importance of the various influences on the environment will depend heavily on detailed sedimentological studies such as those being undertaken by Professor Walker on the laminations of Lake Barrine in northeastern Queensland (Walker 1988) and on fine resolution pollen and charcoal analyses in association with time series analysis as in the study of Bega Swamp by Gurdip Singh and associates (Green *et al.* 1988). For the late Pleistocene, laminated sediments in the Burdekin Delta, that accumulated prior to the last marine incursion, provide one source of information that is being considered for investigation.

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ENSO AND THE HOLOCENE CLIMATES AND FIRE HISTORY OF NEW ZEALAND

Matt S. McGlone, DSIR Land Resources, Christchurch, New Zealand.

M.Jim Salinger, National Climate Centre, Meteorological Service, Wellington, New Zealand.

ENSO and present New Zealand weather

Variations in the Southern Oscillation Index (SOI) have a strong effect on New Zealand weather, although long-range forcasts are only possible when the SOI deviates markedly from the long-term average (Gordon 1985; Kidson and Gordon 1986). Because of the northeast-southwest trending spine of tall mountains which run the length of the southern two-thirds of the New Zealand archipelago, and the strong mid-latitude westerly windflow over the country, SOI variations produce their effect largely through varying the strength and direction of the mean airflow.

During negative SOI episodes (El Niños) mean windflow over New Zealand tends more towards the southwest, a consequence of higher pressures than normal over southeastern Australia and lower pressures to the southeast of New Zealand. Westerlies also strengthen. Increased southwesterly flow brings colder air over the entire country, temperatures tend to be lower than average, and snowfall heavier in the mountains. However, increased westerly windflow across the major mountain ranges produces warming foehn winds in their lee, offsetting to some extent the effect of colder southerly winds on the annual average in the east. Rainfall increases in the south and west of the South Island and becomes lower in eastern districts and the North Island in general, but particularly the northeast. Negative SOIs also tend to bring higher pressures and more settled weather to the northern North Island.

Positive SOI episodes (La Niñas) reverse the windflow pattern anomaly, as there are lower pressures than normal in the central Tasman, bringing more northerly and northeasterly windflow. As a consequence, temperatures are higher. The northeast is wetter and warmer, while the southwest is drier. La Niñas can bring southerly outbreaks behind the low pressure systems as they cross the south of the country.

Extreme El Niño episodes will create severe drought conditions, in particular in the east of both islands where lower rainfall combines with increased drying foehn winds to deplete soil moisture.

Historical records

El Niño events have been associated with severe droughts in New Zealand, particularly in 1877-1878, 1982-1983 and 1987-1988. La Niña events have been associated with excessively wet, cloudy weather in the northeast of the North Island. Clearly much of the interannual variation in both temperature and precipitation can be attributed in part to SOI fluctuations. Recent

dendrochronological analyses of Nothofagus trees in the South Island have revealed a concentration of variance in the reconstructed temperature record at around 3 years, as do time series of variables associated with the SOI (Norton et al, 1989). To our knowledge, this is the only high resolution palaeoclimatic record in New Zealand which shows a link with SOI variations.

Holocene climates and ENSO.

Evidence for Holocene climate variations in New Zealand is largely based on glacier fluctuations, peat bog and lake distribution and growth, pollen analyses, and charcoal (McGlone 1988) and limited isotopic analyses (Hendy and Wilson 1968)

Between 10 000 and 7000 years ago, New Zealand glaciers had shrunk back to their Holocene minimum and isotopic analyses show annual temperatures to have been 1-2 ^{0} C higher. There is no evidence that treelines were any higher than at present. High altitude forests lacked Nothofagus, which is abundant at most locations today, and had greater representation of treeferns. The apparent conflict between glacier and isotopic evidence for warmer temperatures, and static or lower treelines may be resolved by assuming that cloudy, mild summer conditions restricted the energy balance of high altitude plants. In the lowland west, north and south of the country the vegetation reflects mild, highly oceanic climates. In eastern districts, absence or slow growth of peat bogs and restriction of moisture-demanding plants suggest drier climates overall. Peat bogs were generally lacking from high mountains throughout New Zealand, indicating drier winter climates.

After 7000 years ago advance of glaciers and spread of more cold- and drought-tolerant tree species suggest cooler, more variable, more seasonal climates. Fire, as indicated by soil charcoal and airborne fragments in pollen profiles, increased during the late Holocene in eastern districts. At the same time, peat bogs and lakes spread in mountain and lowland districts alike.

Pittock and Salinger (1982) suggested that New Zealand and Australian palaeoclimatic evidence pointed to a dominant positive SOI during the early Holocene. Certainly the warmer conditions and drier far south of the South Island and weaker westerly winds at this time are consistent with a dominant positive phase SOI. However, more important is the lack of variation in the climate, weaker southwesterly windflow and high oceanicity which suggests severe El Niño events were either rare or absent during the early Holocene. On the other hand, the outbreak of fire, spread of drought-resistant trees, and increasing variablity and seasonality strongly suggests that the cooling climates of the late Holocene were accompanied by the establishment of the familiar pattern of accentuated swings between positive and negative phases of the SOI.

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CLIMATE AND FISHERIES: CAUSE AND EFFECT
Long and Short Term Patterns and Processes

by Gary D. Sharp

Center for Climate-Ocean Resources Studies
P. O. Box 2223, Monterey, CA 93940
or
Visiting Scientist, NOAA Center for Ocean
Analysis and Prediction
NPS/FNOC, Bldg 4, Monterey, CA 93943-5005

ABSTRACT

Fisheries and society have clearly been shaped by both long and short term climate and weather patterns, on local, regional and global scales. The recent convergence of many research sciences on these climate-driven processes has made it possible to begin to attribute many of the various marine population responses to common causal climate patterns. Among the most recent popular issues has been the study of El Nino, the warm phase of a much more complex set of relations between ENSO and global and regional events, particularly with respect to fisheries and global heat budgets and consequential flood/drought cycles. A review of the various types and scales of responses by pelagic fish populations to these issues provides the insights into the scales and great complexities of how species and populations are affected over short and long term, and how man fits into the scheme of global climate issues.

Paleoclimate Data Management and the NOAA/NGDC Program in Paleoclimatology

Troy L. Holcombe
NOAA/National Geophysical Data Center
325 Broadway
Boulder, CO 80303

The NOAA/NGDC Program in Paleoclimatology has as its objectives to (1) establish and build the global paleoclimate data base, and (2) carry on a research program to use the developing data base for the study of global climate change. A specific long-term objective is to develop climate reconstructions, using the combined global array of paleoclimate data, for testing and validation of GCM's.

Work on the first objective has been in progress for almost two years and has concentrated on the acquisition of relatively complete, well-documented, and easily available data sets. At the same time planning has proceeded with the assistance of the NOAA Paleoclimate Advisory Panel.

Investigations of data sources have resulted in the compilation of catalogs and bibliographies of ice cores, lake varves, and marine varves. NGDC has assumed responsibility for operation of the International Tree-Ring Data Bank, under the continuing oversight of the ITRDB Advisory Committee. In cooperation with LTRR University of Arizona, new tree-ring chronologies are being developed from the vicinity of Elk Lake, Minnesota for intercomparison with long instrumental records and with climate-related measurements from the 10,000 year-long Elk Lake varve sequence.

Data sets already in hand include tree-ring data, sunspot numbers, CLIMAP 18,000 yr BP and 120,000 yr BP, data sets, radiocarbon dates, SPECMAP archive no. 1, Insolation and orbital variation information, CaCO3 percentages in marine sediments, and ice core measurements. Paleoclimate data present no unusual problems in the realm of data management. Of greater concern are deciding what should go into the data base, how to read the climate signals contained in various proxy data, and how to derive regional and global climate reconstructions from such a diverse array of paleoclimate data.

Address List

Dr. Rob Allan
Division of Atmospheric Research
CSIRO
Private Bag #1
Mordialloc, Victoria 3195
AUSTRALIA
61-3-586-7666 FAX: 61-3-586-7600

Dr. R.Y. Anderson
Department of Geology
University of New Mexico
Albuquerque, N.M. 87131
(505)-277-1639

Dr. Timothy Baumgartner
CICESE
P.O. Box 4844
San Ysidro, CA 92073
(706)-678-6433

Dr. Daniel Cayan
Climate Group A-024
Scripps Institution of Oceanography
UCSD
La Jolla, CA 92093
(619)-534-4507

Dr. Malcolm Cleaveland
Department of Geography
University of Arkansas
Fayetteville, AR 72701
(501)-575-3159

Ms. Julia Cole
Lamont Doherty Geological Observatory
Palisades NY 10964
(914)-359-2900

Mr. Ed Cook
Lamont-Doherty Geological Observatory
Palisades, NY 10964
(914)-359-2900

Dr. Roseann D'Arrigo
Lamont-Doherty Geological Observatory
Palisades, N.Y. 10964
(914)-359-2900

Dr. Walter Dean
USGS
Mail Stop 940
Box 25046
Lakewood, CO 80225
(303)-236-1644

Dr. Henry F. Diaz
NOAA/ERL
325 Broadway
Boulder CO 80303
(303)-497-6649 (FTS: 320-6649)

Dr. David B. Enfield
NOAA/AOML
4301 Rickenbacker Causeway
Miami, FL 33149
(305)-361-1351 (FTS: 350-1351)

Dr. Nicholas E. Graham
Climate Group A-024
Scripps Institution of Oceanography
UCSD
La Jolla, CA 92093
(619)-534-4507

Dr. Troy L. Holcomb
Mail Code E/GC3
National Geophysical Data Center
325 Broadway
Boulder, CO 80303
(303)-497-6390

Dr. Malcolm K. Hughes
Tree Ring Laboratory
University of Arizona
Tucson, Arizona 85721
(602)-621-2191

Dr. Thomas Johnson
Duke Marine Laboratory
Beaufort, NC 28516
(919)-728-2111

Dr. Paul Kay
Department of Geography
University of Nebraska-Lincoln
311 Avery Hall
Lincoln, NE 68588
(402)-472-2865

Dr. P. Kershaw
Dep. Geography
Monash University
Clayton, Victoria 3168
AUSTRALIA
61-3-5654000

Dr. Janice Lough
Australian Institute of Marine Science
PMB #3
Townsville, M.C.
Queensland 4810
AUSTRALIA
61-77-789211

Dr. Vera Markgraf
INSTAAR CB-450
University of Colorado
Boulder, CO 80309
(303)-492-5117

Dr. Mat McGlone
DSIR
Private Bag
Christchurch, New Zealand
64-3-252-511

Dr. Gerald A. Meehl
National Center for Atmospheric
Research
P.O. Box
Boulder, CO 80307
(303)-497-1331

Dr. David Meko
Tree Ring Laboratory
University of Arizona
Tucson, AZ 85721
(602)-621-7680

Dr. Joel Michaelsen
University of California-Santa Barbara
Department of Geography
Santa Barbara, CA 93106
(805)-961-2296

Dr. Neville Nicholls
Bureau of Meteorology Research Centre
GPO Box 1289K
Melbourne, VIC 3001
AUSTRALIA
61-3-6694000

Dr. William H. Quinn
College of Oceanography
Oregon State University
Corvallis, OR 97331
(503)-754-3504

Dr. Geoffrey Seltzer
Limnological Research Center
Pillsbury Hall
University of Minnesota
Minneapolis, MN 55455
(612)-373-3379

Dr. Gary Sharp
NOAA/COAP
NPS/FNOC, Bldg. 4
Monterey, CA 93943-5005
(408)-646-8023

Dr. Glen Shen
Department of Oceanography
University of Washington
Seattle Washington 98195
(206)-543-3153

Dr. Andy Soutar
Scripps Institution of Oceanography
Mail Code A-014
La Jolla, CA 92037
(619)-534-2171

Dr. David W. Stahle
Department of Geography
University of Arkansas
Fayetteville, AR 72701
(501)-575-3159

Dr. Tom Swetnam
Tree Ring Laboratory
University of Arizona
Tucson Arizona 85721
(602)-621-2112

Dr. Lonnie Thompson
Byrd Institute of Polar Studies
Ohio State University
Columbus Ohio 43210
(614)-292-6531

Dr. Robert H. Webb
U.S. Geological Survey
Water Resources Div.
300 West Congress, FB 44
Tucson, Arizona 85701
(602)-629-6821 (FTS: 762-6821)

Dr. Lisa Wells
Department of Geography
University of California-Berkeley
Berkeley, CA 94717
(415)-642-1281